US011266475B2

(12) United States Patent
Gomez et al.

(10) Patent No.: US 11,266,475 B2
(45) Date of Patent: Mar. 8, 2022

(54) **REPOSITIONING SYSTEM FOR A REMOTELY CONTROLLABLE MANIPULATOR AND RELATED METHODS**

(71) Applicant: **Intuitive Surgical Operations, Inc.**, Sunnyvale, CA (US)

(72) Inventors: **Daniel H. Gomez**, Los Gatos, CA (US); **John Ryan Steger**, Sunnyvale, CA (US)

(73) Assignee: **Intuitive Surgical Operations, Inc.**, Sunnyvale, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 368 days.

(21) Appl. No.: **16/484,299**

(22) PCT Filed: **Dec. 11, 2017**

(86) PCT No.: **PCT/US2017/065522**

§ 371 (c)(1),
(2) Date: **Aug. 7, 2019**

(87) PCT Pub. No.: **WO2018/147930**

PCT Pub. Date: **Aug. 16, 2018**

(65) **Prior Publication Data**

US 2021/0128262 A1 May 6, 2021

Related U.S. Application Data

(60) Provisional application No. 62/456,430, filed on Feb. 8, 2017.

(51) **Int. Cl.**
A61B 34/00 (2016.01)
A61B 34/30 (2016.01)
(Continued)

(52) **U.S. Cl.**
CPC ***A61B 34/74*** (2016.02); *A61B 34/35* (2016.02); *A61B 2034/302* (2016.02); *A61B 2090/508* (2016.02); *A61B 2090/571* (2016.02)

(58) **Field of Classification Search**
CPC combination set(s) only.
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,279,309 A 1/1994 Taylor et al.
5,695,500 A 12/1997 Taylor et al.
(Continued)

FOREIGN PATENT DOCUMENTS

WO WO-2018052795 A1 3/2018
WO WO-2018067696 A1 4/2018

OTHER PUBLICATIONS

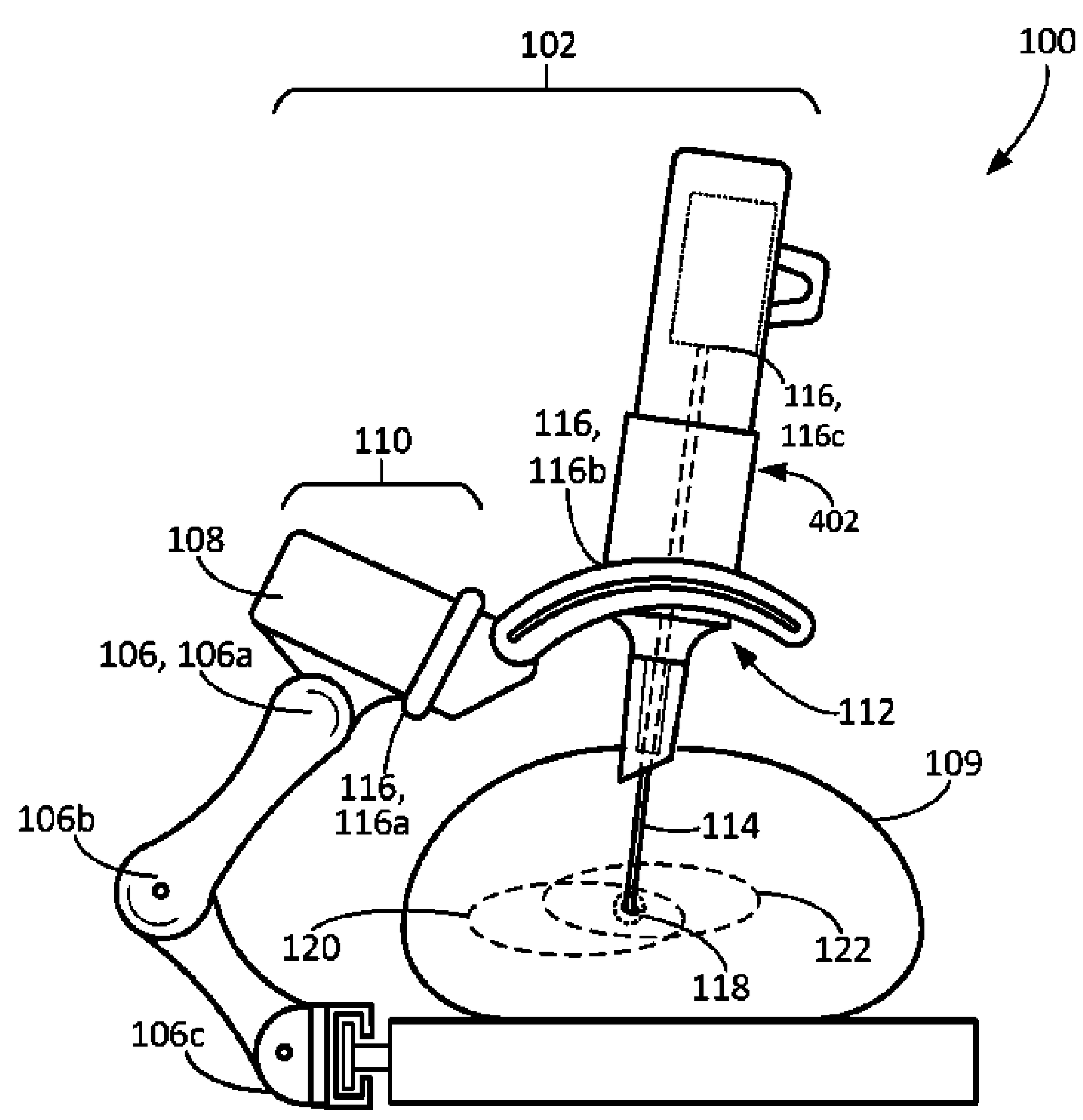
Extended European Search Report for Application No. EP17896089.4 dated Jan. 17, 2020, 9 pages (P00806-EP).
(Continued)

Primary Examiner — Scott Luan
(74) *Attorney, Agent, or Firm* — Fish & Richardson P.C.

(57) **ABSTRACT**

A computer-assisted system comprises a manipulator configured to support a tool, a lockable joint, and a controller. The manipulator extends distally from a base and comprises a distal portion. The lockable joint is coupled to the base and located proximally relative to the base. The controller is operably coupled to a powered joint. The powered joint is located distally relative to the base. The controller is configured to perform operations. The operations comprise: driving the powered joint to move the distal portion while the lockable joint is locked, and driving the powered joint to move the base while the lockable joint is unlocked and a position of the distal portion is externally maintained. A method includes processes for operating a computer-assisted system. A method includes determining a desired motion envelope for a tool supported by a manipulator, and positioning a base of the manipulator based on the desired motion envelope.

27 Claims, 10 Drawing Sheets



(51) **Int. Cl.**

A61B 34/35	(2016.01)
A61B 90/50	(2016.01)
A61B 90/57	(2016.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2007/0013336	A1	1/2007	Nowlin et al.
2011/0277775	A1	11/2011	Holop et al.
2014/0039517	A1	2/2014	Bowling et al.
2016/0081753	A1	3/2016	Kostrzewski et al.
2016/0113728	A1	4/2016	Piron et al.

OTHER PUBLICATIONS

International Search Report and Written Opinion for Application No. PCT/US2017/065522, dated Jul. 5, 2018, 23 pages.

Vertut, Jean and Phillipe Coiffet, Robot Technology: Teleoperation and Robotics Evolution and Development, English translation, Prentice-Hall, Inc., Inglewood Cliffs, NJ, USA 1986, vol. 3A, 332 pages.

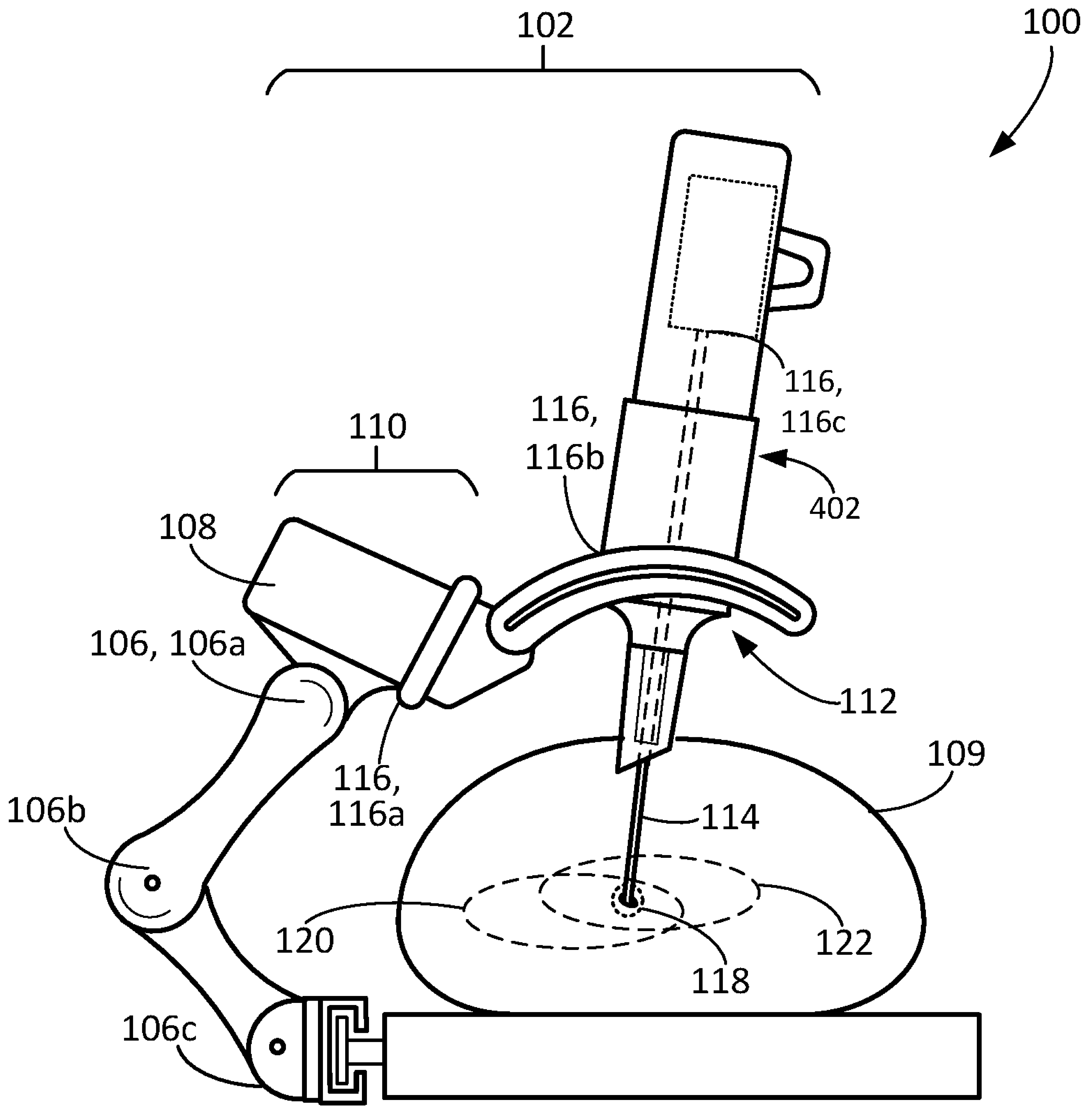

102
100
116,
116c
116,
116b
402
110
108
106, 106a
112
109
116,
116a
106b
114
120
122
118
106c

FIG. 1

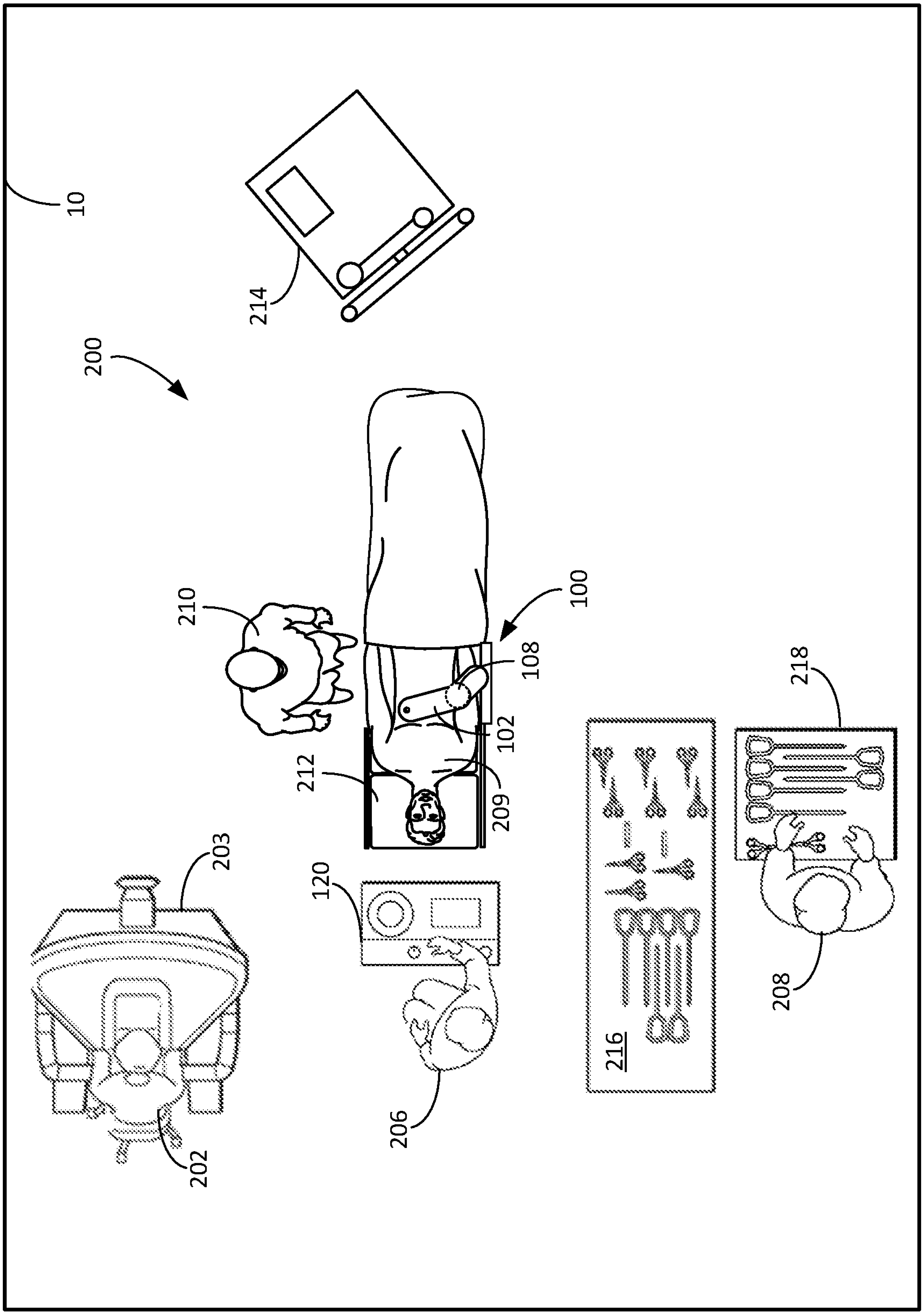


FIG. 2

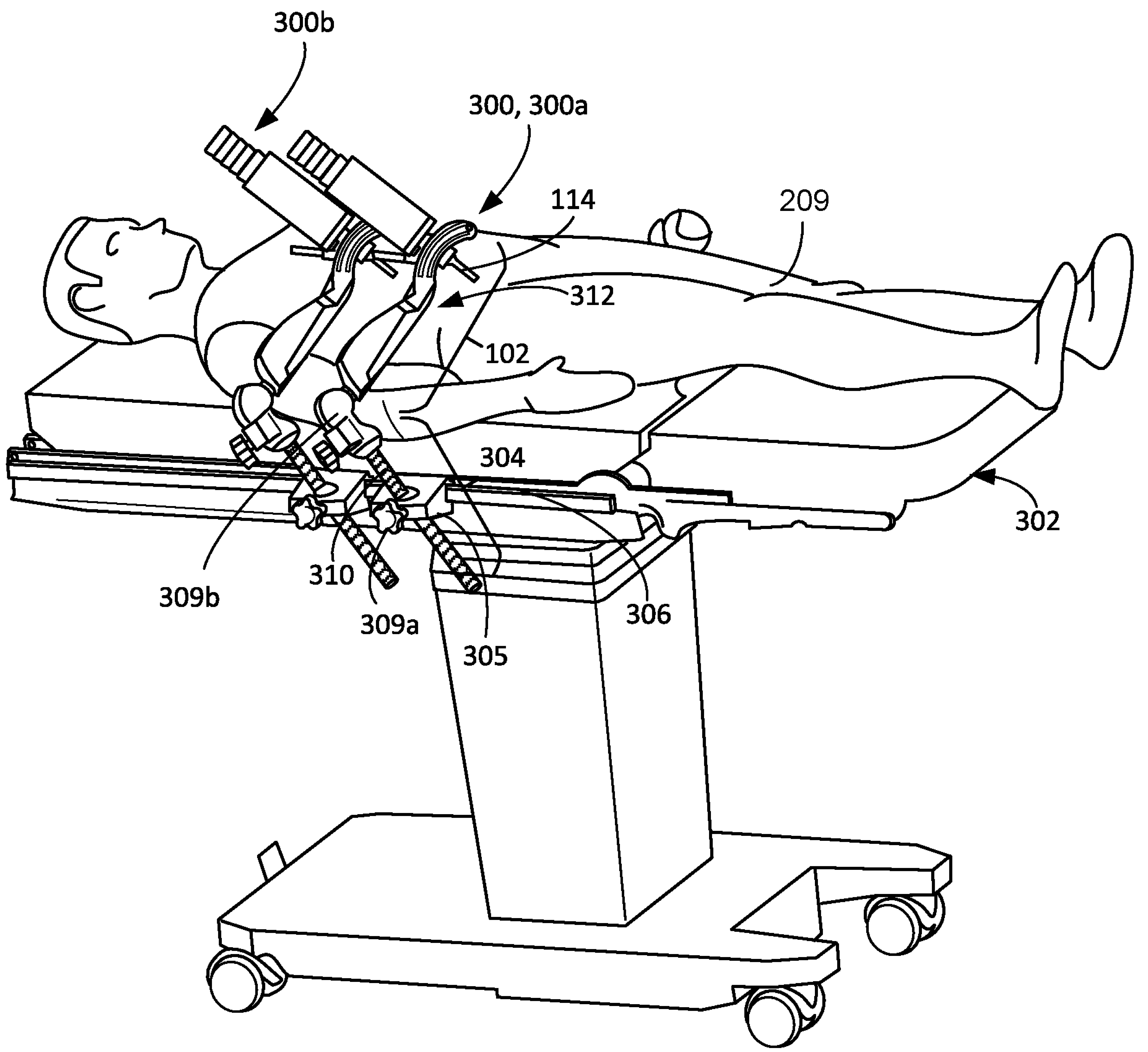


FIG. 3

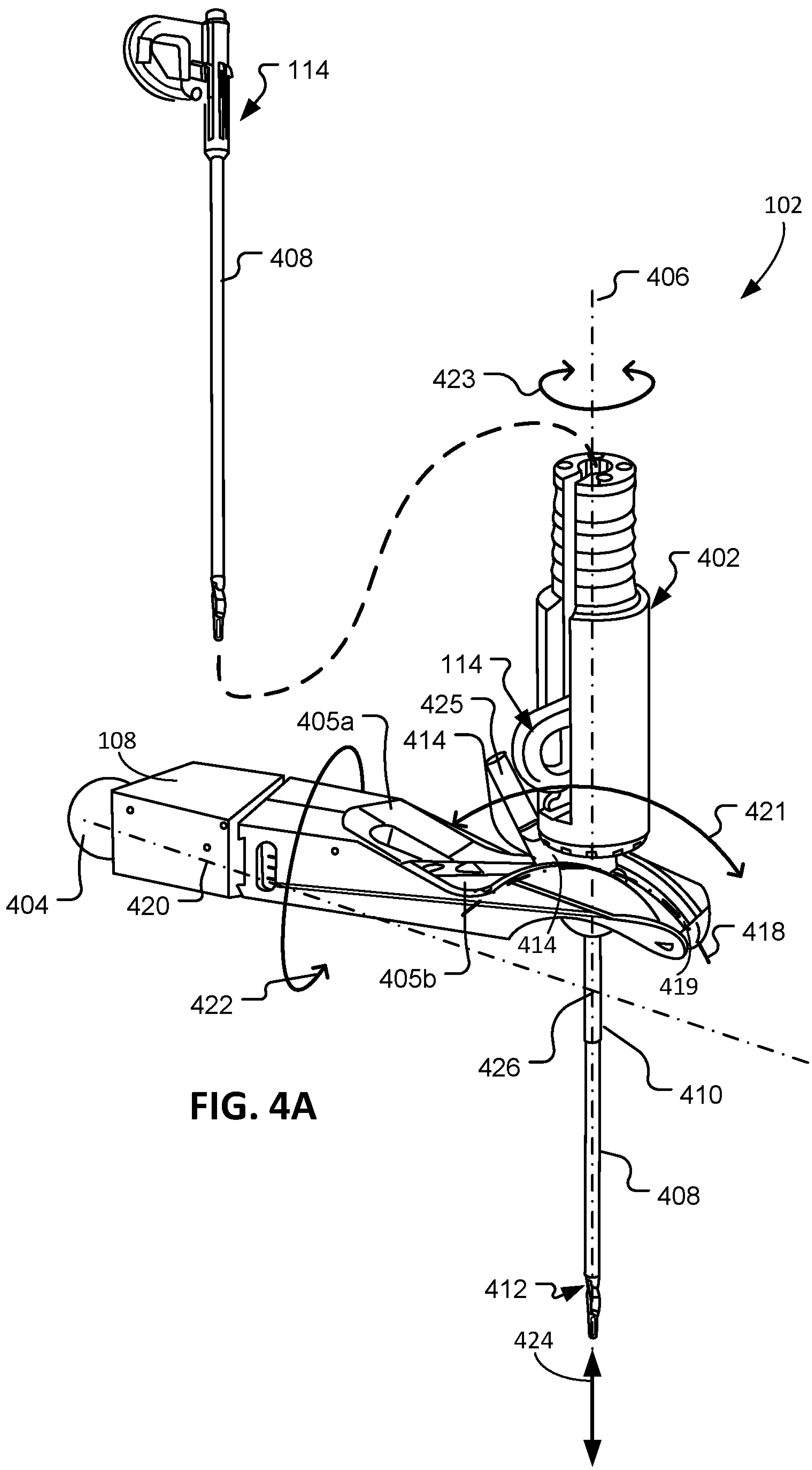

114
408
102
406
423
402
114
425
405a
414
108
421
404
420
414
418
405b
419
422
426
410
408
412
424

FIG. 4A

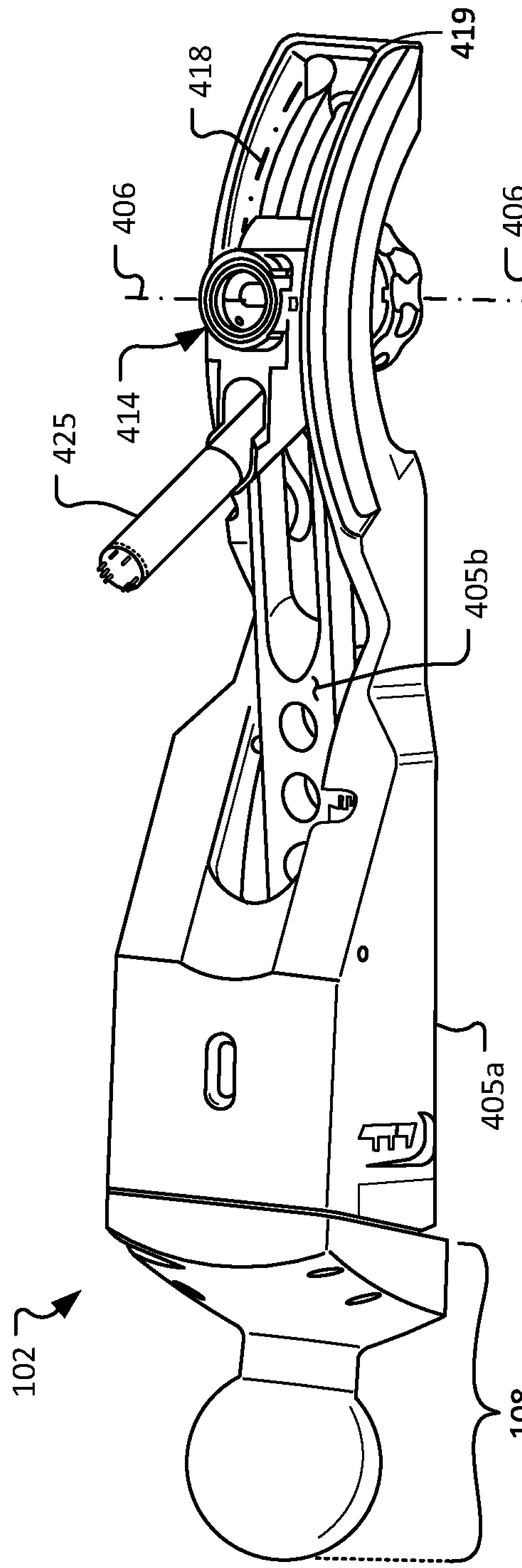

419
418
406
406
414
425
405b
405a
102
108

FIG. 4B

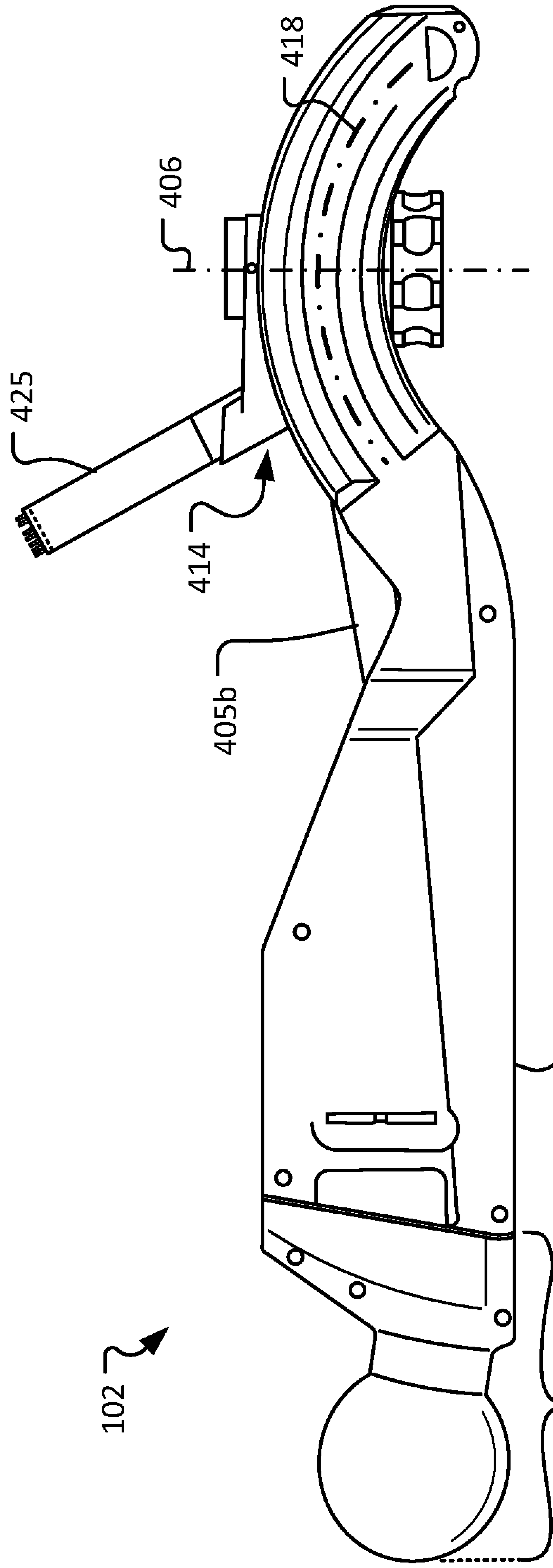

418
406
425
414
405b
405a
102
108

FIG. 4C

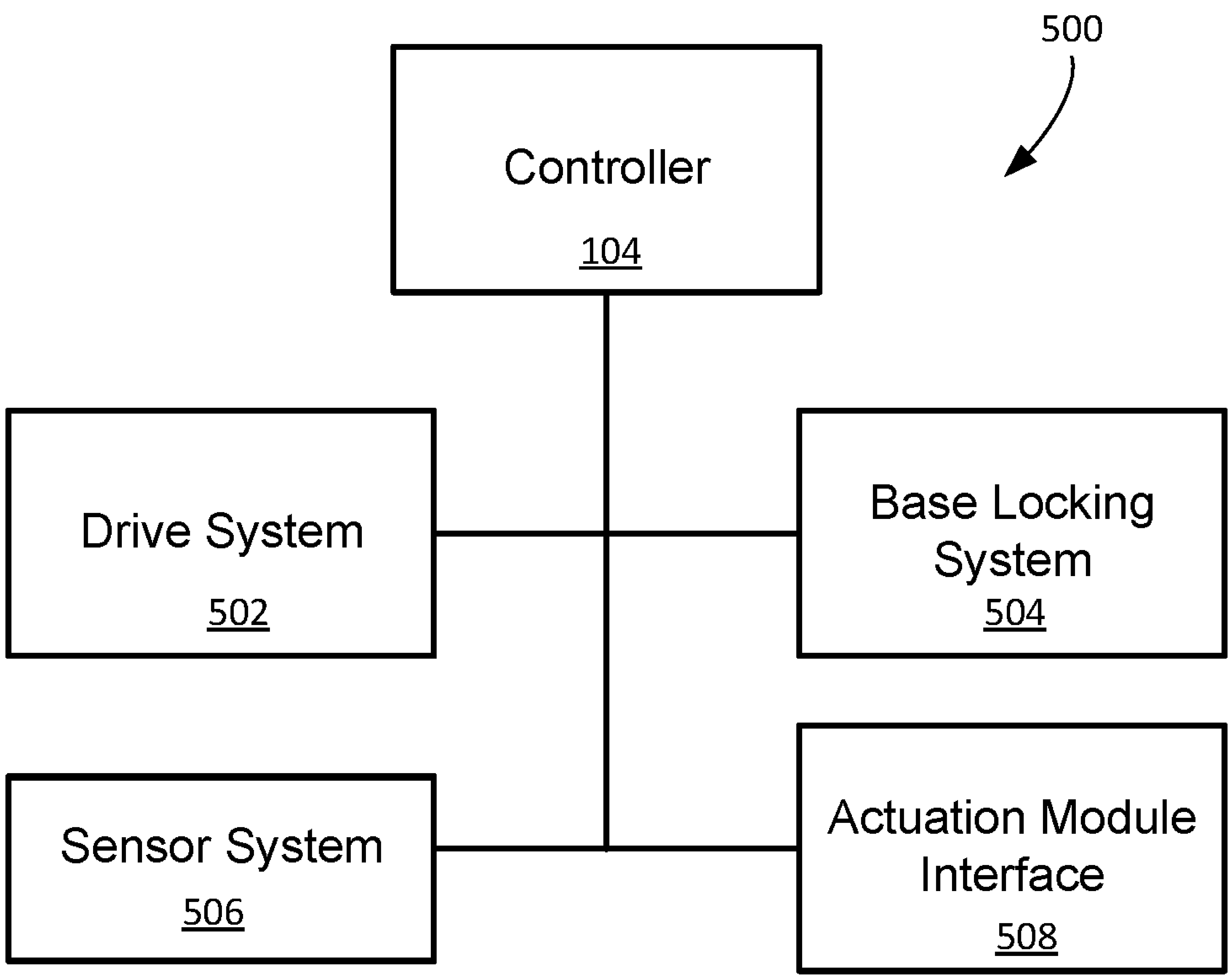

500
Controller
104
Drive System
502
Base Locking
System
504
Sensor System
506
Actuation Module
Interface
508

FIG. 5

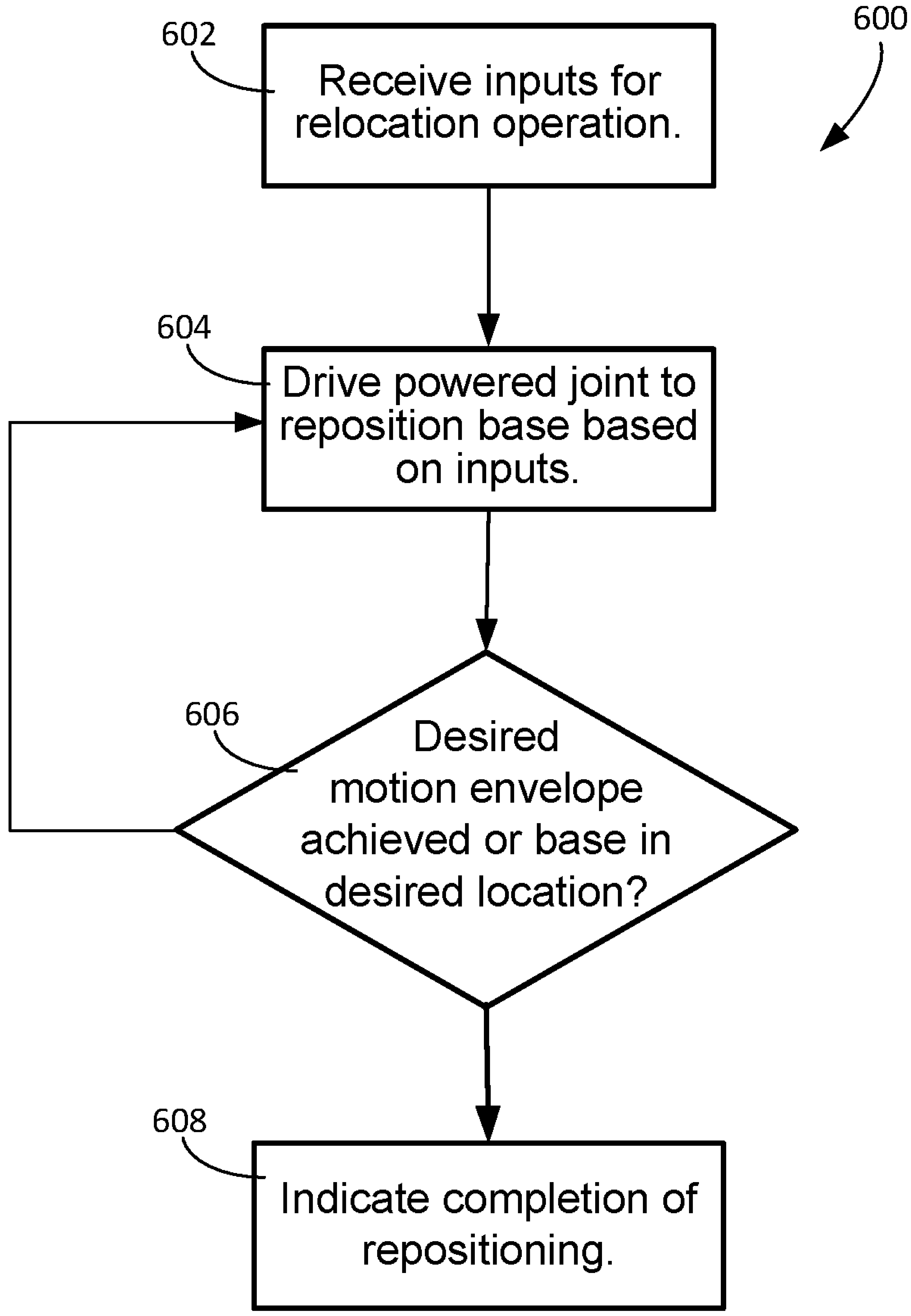

600
602
Receive inputs for relocation operation.
604
Drive powered joint to reposition base based on inputs.
606
Desired motion envelope achieved or base in desired location?
608
Indicate completion of repositioning.

FIG.6

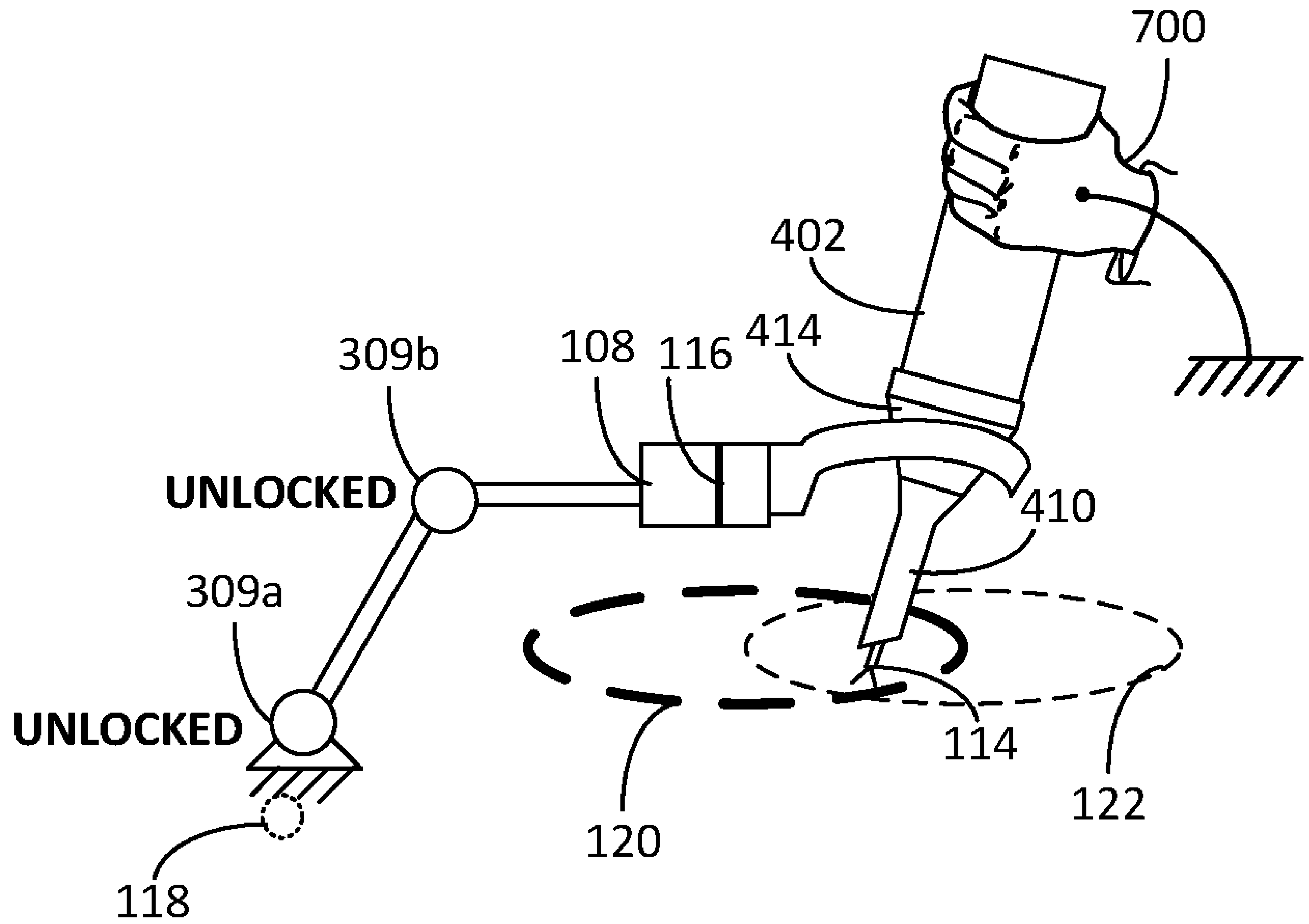

700
402
309b
108
116
414
UNLOCKED
410
309a
UNLOCKED
114
122
120
118

FIG. 7A

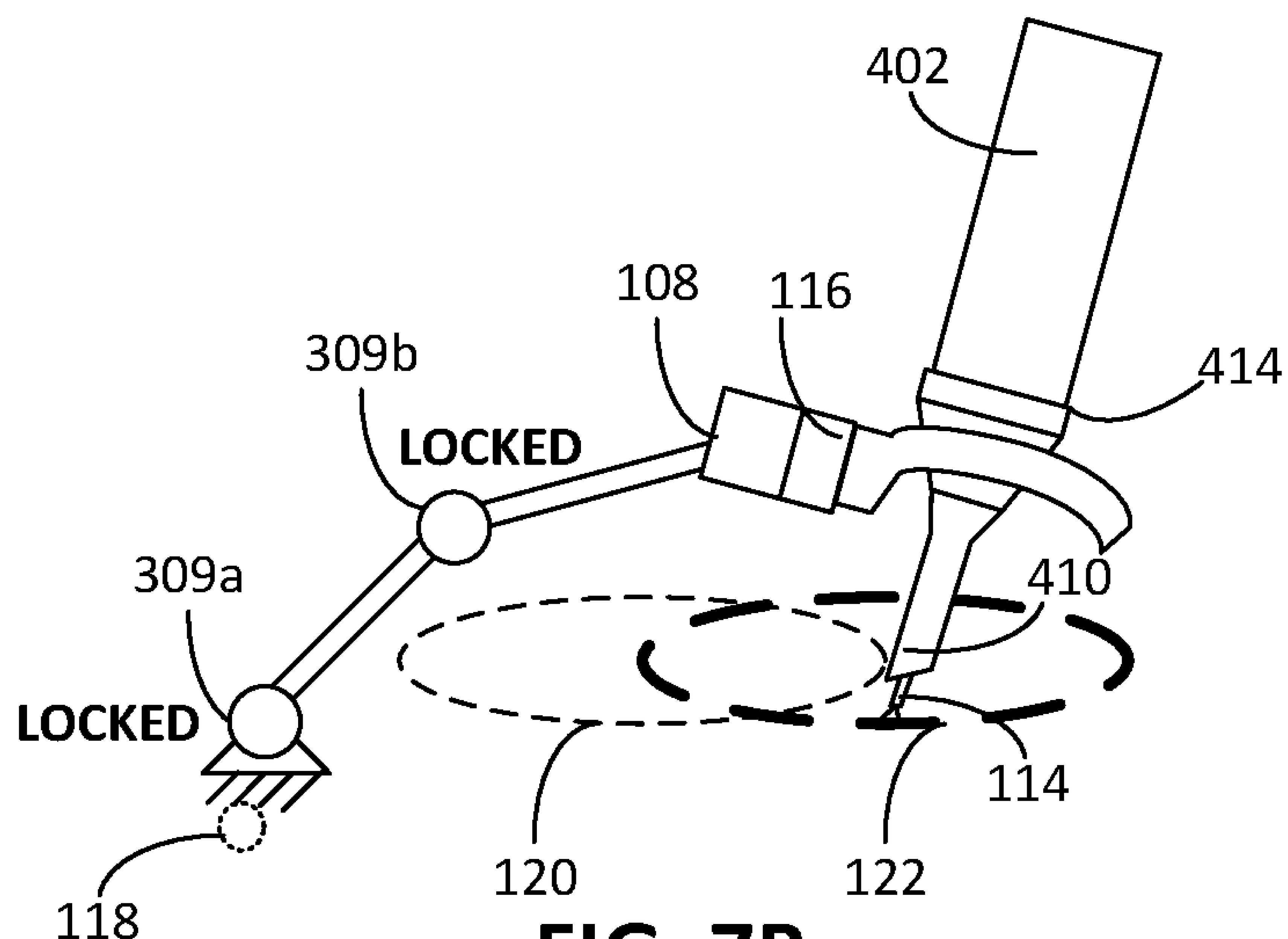

402
108
116
309b
414
LOCKED
309a
410
LOCKED
114
120
122
118

FIG. 7B

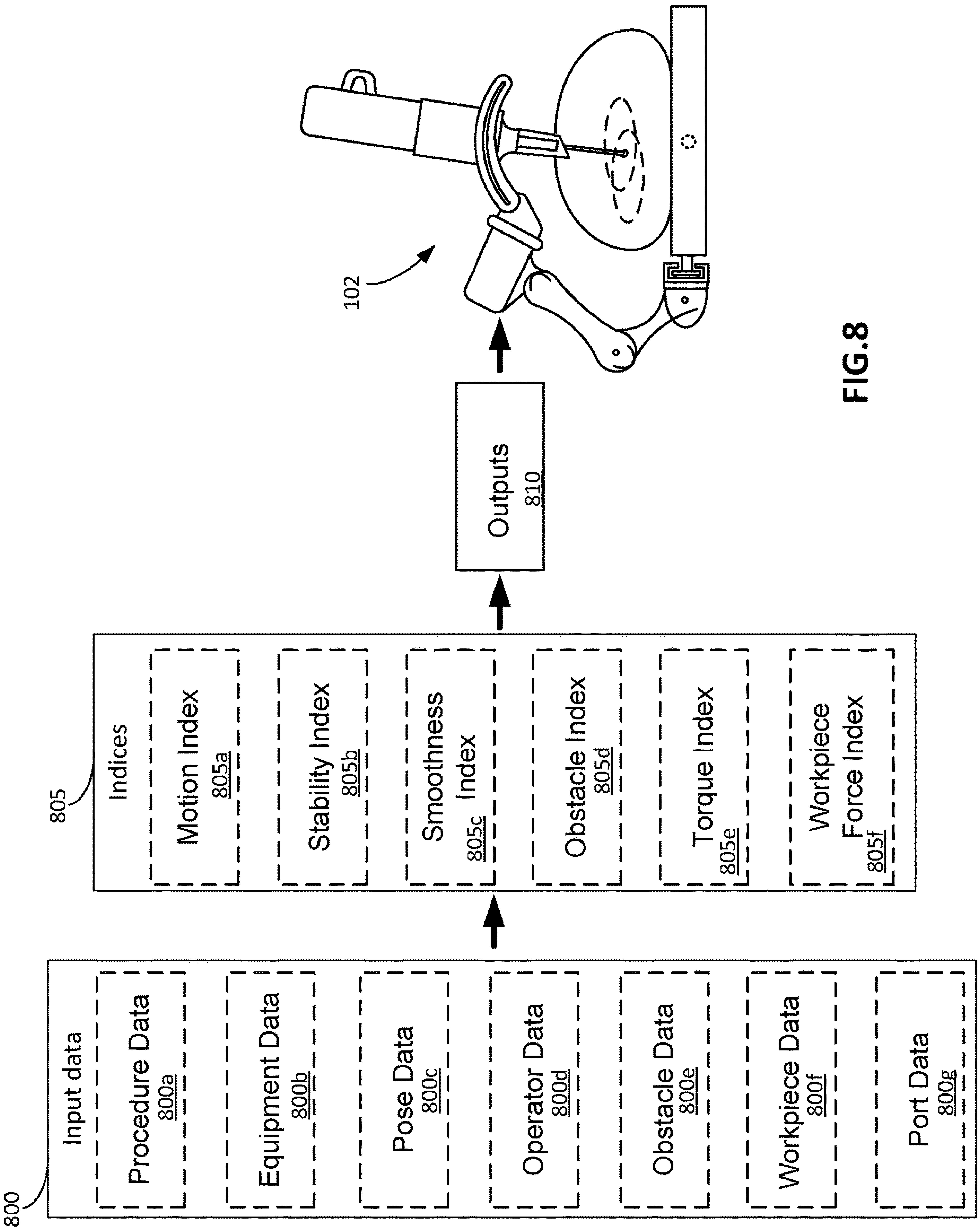
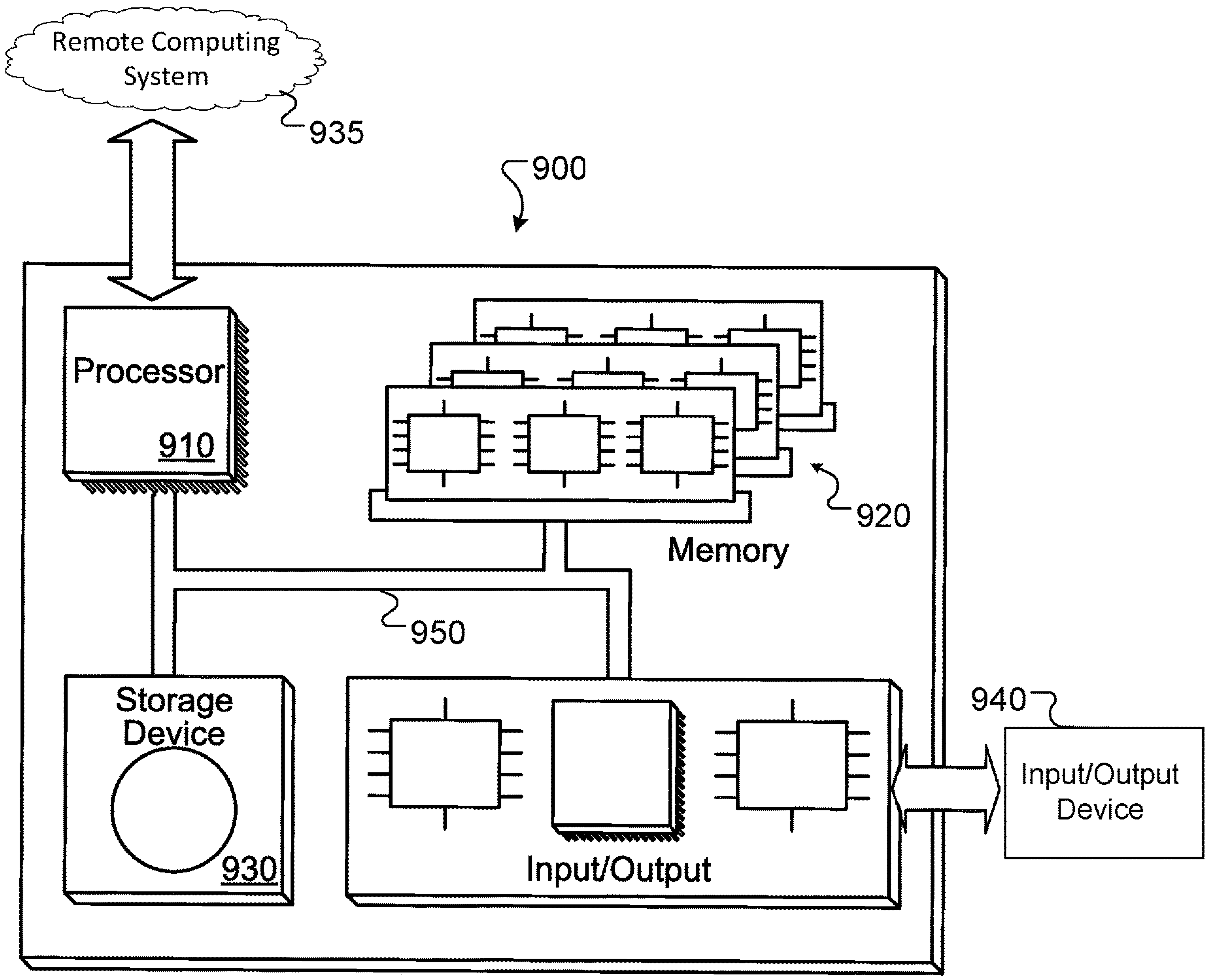

800
Input data
Procedure Data
800a
Equipment Data
800b
Pose Data
800c
Operator Data
800d
Obstacle Data
800e
Workpiece Data
800f
Port Data
800g
805
Indices
Motion Index
805a
Stability Index
805b
Smoothness Index
805c
Obstacle Index
805d
Torque Index
805e
Workpiece Force Index
805f
Outputs
810
102

FIG.8



Remote Computing System
935
900
Processor
910
920
Memory
950
Storage Device
930
940
Input/Output
Input/Output Device

FIG. 9

REPOSITIONING SYSTEM FOR A REMOTELY CONTROLLABLE MANIPULATOR AND RELATED METHODS

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a U.S. National Stage Application under 35 U.S.C § 371 and claims the benefit of International Patent Application No. PCT/US2017/065522, filed on Dec. 11, 2017, which claims the benefit of U.S. Provisional Application No. 62/456,430, filed on Feb. 8, 2017. The disclosures of the prior applications are considered part of and are incorporated herein by reference in the disclosure of this application.

TECHNICAL FIELD

This specification relates to a system for a manipulator such as a remotely controllable manipulator.

BACKGROUND

Robotic systems can include robotic manipulators to manipulate tools for performing a task at a work site. The robotic manipulator can include two or more links coupled together by one or more joints. The joints can be active joints that are actively controlled. The joints can also be passive joints that may comply with movement of the active joints as the active joints are actively controlled. Such active and passive joints may be revolute or prismatic joints. The configuration of the robotic manipulator may then be determined by the positions of the joints, the structure of the robotic manipulator, and the coupling of the links.

Robotic systems include industrial and recreational robotic systems. Robotic systems also include medical robotic systems used in procedures for diagnosis, non-surgical treatment, surgical treatment, etc. As a specific example, robotic systems include minimally invasive, computer-assisted, robotic surgical systems in which a surgeon can operate on a patient from bedside or a remote location. Telesurgery refers generally to surgery performed using surgical systems where the surgeon uses some form of remote control, e.g., a servomechanism, to manipulate surgical tool movements rather than directly holding and moving the surgical tools by hand. A robotic surgical system usable for telesurgery can include a remotely controllable robotic manipulator. Operators can remotely control motion of the robotic manipulator. Operators can also manually move pieces of the robotic surgical system into positions within a surgical environment. For example, a surgeon, a surgical assistant, or other operator can push or pull the equipment by hand such that the equipment moves along a floor surface of the surgical environment.

SUMMARY

In one aspect, a computer-assisted system comprises a manipulator configured to support a tool, a lockable joint, and a controller. The manipulator extends distally from a base and comprises a distal portion. The lockable joint is coupled to the base and located proximally relative to the base. The controller is operably coupled to a powered joint. The powered joint is located distally relative to the base. The controller is configured to perform operations. The operations comprise: driving the powered joint to move the distal portion while the lockable joint is locked, and driving the powered joint to move the base while the lockable joint is unlocked and a position, an orientation, or both position and orientation parameters is externally maintained.

In another aspect, a method for operating a computer-assisted system comprises driving a powered joint to move a base while a lockable joint is unlocked and a position, an orientation, or both position and orientation parameters of a distal portion of a manipulator is externally maintained, and driving the powered joint to move the distal portion while the lockable joint is locked. The computer-assisted system comprises the manipulator and the lockable joint. The manipulator extends distally from a base. The lockable joint is coupled to the base and located proximally relative to the base. The powered joint is located distally relative to the base.

In another aspect, a non-transitory machine-readable medium comprises a plurality of machine-readable instructions. These instructions are adapted, when executed by one or more processors are, to cause the one or more processors to perform any of the methods disclosed herein.

For example, in one aspect, these instructions are adapted to cause one or more processors to perform a method for operating a computer-assisted system. The computer-assisted system comprises a manipulator and a lockable joint. The manipulator extends distally from a base. The lockable joint is coupled to the base and located proximally relative to the base. The method comprises: determining a desired location for the base, driving a powered joint to backdrive the base toward the desired location while the lockable joint is unlocked and a position, an orientation, or both position and orientation parameters of a distal portion of the manipulator is externally maintained, and (after the lockable joint is locked) driving the powered joint to move the distal portion. The powered joint is located distally relative to the base.

In yet another aspect, a computer-assisted surgical system includes a remotely controllable manipulator. The manipulator extends from a base of the manipulator to a distal portion including a coupling configured to support a surgical tool. The surgical system further includes a lockable joint at the base of the manipulator. A powered joint distal to the base is drivable to move the surgical tool relative to a reference point within a motion envelope while the lockable joint is locked. The motion envelope is defined in part by a position of the base relative to the reference point. The surgical system further includes a controller operably connected to the powered joint. The controller is configured to change the motion envelope of the surgical tool by driving the powered joint, while the lockable joint is unlocked and while a position of the surgical tool relative to the reference point is maintained, to adjust the position of the base relative to the reference point.

In another aspect, a method includes determining a desired motion envelope for a surgical tool supported by a remotely controllable manipulator. The method further includes driving a powered joint distal to a base of the manipulator to reposition the base relative to an operating table such that a motion envelope of the surgical tool is adjusted based on the desired motion envelope while the base is unlocked and while a position of the surgical tool is maintained.

Some implementations may include one or more of the features described below and herein elsewhere, including any appropriate combination of the implementations described below.

In various implementations, the pose of the distal portion is externally maintained by maintaining, for a part of the distal portion: a position, an orientation, one or more posi-

tion parameters, one or more orientation parameters, both position and orientation, or a combination of position and orientation parameters.

In some implementations, the position of the distal portion is externally maintained relative to a reference point, driving the powered joint to move the distal portion moves the distal portion relative to the reference point, and driving the powered joint to move the base moves the base relative to the reference point. In some implementations, the reference point corresponds to a location of an access port through which the tool accesses a work site. In some implementations, the access port is a minimally invasive access port or an entry to a natural orifice of a patient.

In some implementations, a position of the base is maintained by the lockable joint. For example, locking the lockable joint, or locking a plurality of lockable joints including the lockable joint, locks the position of the base. In some implementations, the position of the distal portion is externally maintained by maintaining a position of the tool or a position of a cannula coupled to the manipulator.

In some implementations, driving the powered joint while the lockable joint is unlocked and the position of the distal portion is externally maintained moves the base by back-driving with the powered joint.

In some implementations, the driving of the powered joint to move the base is slowed or stopped in response a determination that the position of the distal portion is not externally maintained.

In some implementations, the computer-assisted system further comprises an actuation module. The manipulator is configured to couple to the actuation module and support the tool through the actuation module. In some implementations, and the actuation module is configured to translate the tool along a longitudinal axis of the tool, and to drive an end effector of the tool. In some implementations, the actuation module comprises the powered joint.

In some implementations, the manipulator comprises the powered joint.

In some implementations, the method further comprises, or the operations further comprise, driving the powered joint to center the tool within a range of motion of the tool. In some implementations, the driving of the powered joint to center the tool is based on a user selection. In some implementations, driving the powered joint to center the tool comprises driving the powered joint to adjust the position of the base based on a pointing direction of the tool.

In some implementations, driving the powered joint to move the base comprises determining a desired motion envelope, and driving the powered joint to move the base toward a position that provides the desired motion envelope. In some implementations, driving the powered joint to move the base comprises determining a desired location for the base, and driving the powered joint to move the base toward the desired location. The system may stop moving the base once the base reaches, or is within some tolerance of, the position that provides the desired motion envelope or the desired location for the base; or, the system may stop moving the base in response to some other criteria, such as in response to forces or deflections indicative of collision, to a determination of an inability to reach the base position that provides the desired motion envelope or the desired base location, to user input, to lack of user presence, etc.

In various implementations, the desired motion envelope or the desired location for the base is determine based on one or more of the following: a likelihood of collision of the manipulator, a pose of the manipulator relative to a pose of a second manipulator of the computer-assisted system, a motion envelope of a setup joint of the manipulator, a type of operation to be performed, a likelihood of collision of the manipulator. The second manipulator may be coupled to the same base as the first manipulator, or to a second base separate and moveable relative to the base of the first manipulator.

In some implementations, driving the powered joint to move the base while the lockable joint is unlocked comprises driving the powered joint to adjust the position of the base based on a pointing direction of the tool. In some implementations, driving the powered joint based on a pointing direction of the tool comprises driving the powered joint while an insertion axis of the tool is directed toward a target. In some implementations, adjusting the position of the base based on the pointing direction of the tool facilitates centering the tool within its range of motion or motion envelope.

In some implementations, the operations further comprise, or the method further comprises driving a second powered joint coupled to the base and located distally relative to the base. For example, the powered joint and a second powered joint are both driven to move the distal portion while the lockable joint is locked. And, the powered joint and a second powered joint are both driven to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained.

In some implementations, the computer-assisted system further comprises one or more additional lockable joints that are unlocked when driving the powered joint to move the base, and/or are locked when driving the powered joint to move the base. For example, in one implementation, the computer-assisted system further comprises a second lockable joint, and driving the powered joint to move the base comprises driving the powered joint to reposition the lockable joint and the second lockable joint while both the lockable joint and the second lockable joint are unlocked.

In some implementations, the computer-assisted system further a setup assembly configured to couple the base to a table, where the setup assembly comprises the lockable joint.

In some implementations, the computer-assisted system further comprises a sensor configured to generate a signal in response to detecting that the position of the distal portion is externally maintained. And, the powered joint is driven to move the base in response to the signal.

In some implementations, the computer-assisted system further comprises a sensor configured to generate a signal in response to detecting that the lockable joint is locked. And, the powered joint is driven to move the distal portion in response to the signal.

In some implementations, the lockable joint is manually locked, manually unlocked, or both manually locked and unlocked.

In some implementations, the method further comprises, or the operations further comprise, unlocking the lockable joint after driving the powered joint to move the base. In some implementations, the method comprises, or the operations comprise, selectively unlocking or locking the lockable joint while driving the powered joint to move the base, while the position of the distal portion is externally maintained.

In some implementations, the method further comprises, or the operations further comprise, inhibiting motion of the base in response to a determination that a motion envelope of the tool is approaching a desired motion envelope for the tool.

In some implementations, the controller is configured to change the motion envelope of the surgical tool by driving the powered joint to backdrive the base.

In some implementations, driving the powered joint includes backdriving the base.

In some implementations, the coupling is configured to receive an actuation module operable to drive an end effector of the surgical tool. In some cases, the surgical system further includes the actuation module. The actuation module is, for example, mounted to the coupling of the manipulator, and the actuation module is configured to translate the surgical tool along a longitudinal axis of the surgical tool and to drive the end effector of the surgical tool when the surgical tool is mounted to the actuation module. In some cases, the powered joint includes a powered joint between the actuation module and the surgical tool.

In some implementations, the remotely controllable manipulator includes the powered joint.

In some implementations, a position of the base is fixed relative to the reference point when the lockable joint is locked, and the position of the base is movable relative to the reference point to change the motion envelope of the surgical tool when the lockable joint is unlocked.

In some implementations, the controller is configured to drive the powered joint to center the surgical tool within a range of motion of the surgical tool. In some cases, the controller is configured to drive the powered joint to center the surgical tool based on a user selection.

In some implementations, the controller is configured to change the motion envelope of the surgical tool in accordance to a desired motion envelope based on a type of surgical operation to be performed by the surgical system.

In some implementations, controller is configured to change the motion envelope of the surgical tool in accordance to a desired motion envelope based on a likelihood of collision of the manipulator with an obstacle.

In some implementations, the controller is configured to the drive the powered joint to adjust the position of the base while an insertion axis of the surgical tool is directed toward a target anatomy of a patient, the patient being fixed relative to the reference point.

In some implementations, the manipulator includes a linkage extending between the base and the surgical tool, and the controller is configured to change the motion envelope of the surgical tool by moving the linkage relative to the base.

In some implementations, the controller is configured to drive first and second powered joints to adjust the motion envelope of the surgical tool.

In some implementations, the surgical system further includes a setup assembly including the lockable joint. The setup assembly, for example, supports the manipulator relative to the reference point. The controller is, for example, configured drive the powered joint to reposition the setup joint while the base is movable relative to the reference point, while the setup joint is movable relative to the reference point, and while the position of the surgical tool is maintained.

In some implementations, the controller is configured to drive the powered joint to perform a surgical operation after changing the motion envelope of the surgical tool and after the lockable joint is locked.

In some implementations, the controller is configured to drive the powered joint to adjust the position of the base while a user directs the surgical tool toward target anatomy of a patient.

In some implementations, determining the desired motion envelope includes determining the desired motion envelope based on a motion envelope of a setup joint of the manipulator.

In some implementations, determining the desired motion envelope includes determining the desired motion envelope based on a type of surgical operation to be performed. In some cases, repositioning the base of the manipulator includes driving a powered joint of the manipulator. The method further includes, for example, driving the powered joint to perform the surgical operation on a patient.

In some implementations, determining the desired motion envelope includes determining the desired motion envelope based on a likelihood of collision of the manipulator with an obstacle.

In some implementations, repositioning the base of the manipulator includes repositioning the base of the manipulator while a setup joint of the manipulator is unlocked.

Advantages of the foregoing may include, but are not limited to, those described below and herein elsewhere. The base can be repositioned such that the surgical tool can more easily reach target anatomy during a surgical procedure. For a manipulator system including a setup assembly and the manipulator, the base of the manipulator can be repositioned without a human operator having to manually reposition the base or the setup assembly of the manipulator system. During repositioning of the base, the motion envelope of the surgical tool can be adjusted to reduce a likelihood that the manipulator contacts objects within the surgical environment.

In some examples, actuators in addition to the actuators to reposition the surgical tool are not necessary to reposition the base. The actuators that are used to reposition the surgical tool are also used to reposition the base. These actuators can be actuators kinematically positioned between the surgical tool and the base of the manipulator, thereby preventing a need for external actuators to drive the base.

Although the specific examples presented in this disclosure often discuss surgical examples, the techniques disclosed are also applicable to non-surgical use. For example, they may be used with and improve general or industrial robotic operations, such as those use in manipulating work pieces. These techniques may also be used with and improve medical robotic operations for diagnoses and non-surgical treatment.

Further, although the specific examples presented in this disclosure often discuss teleoperational robotic systems and remotely controllable arms, the techniques disclosed are also applicable to robotic systems that are directly and manually moved by operators, in part or in whole. For example, these techniques can be applied to robotic systems designed to help steady a tool held by the robotic arm while the tool is manipulated hand of an operator.

As another example, any of the controllable arms discussed herein may be configured to allow direct manipulation, and accept operator instruction through input directly applied to a link or a joint of the manipulator.

The details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other potential features, aspects, and advantages will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a side view of an example computer-assisted system with a manipulator.

FIG. 2 is a top view of an example surgical system.

FIG. 3 is a perspective view of an example surgical environment including first and second remotely controllable manipulators.

FIG. 4A is a side perspective view of an example manipulator that can be coupled to a setup assembly.

FIG. 4B is a top perspective view of the manipulator of FIG. 4A.

FIG. 4C is a side view of the manipulator of FIG. 4A.

FIG. 5 is a block diagram of an example computer-assisted system.

FIG. 6 is a flowchart of an example process of relocating a manipulator.

FIGS. 7A and 7B depict an example process of relocating a manipulator.

FIG. 8 is a diagram of example inputs for relocating a manipulator.

FIG. 9 is a diagram of a computer system that can be used to implement a controller described in association with any of the computer-implemented methods described herein.

Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

Although some of the examples described herein refer to surgical procedures or tools, or medical procedures and medical tools, the techniques disclosed apply to non-medical procedures and non-medical tools. For example, the tools, systems, and methods described herein may be used for non-medical purposes including industrial uses, general robotic uses, and sensing or manipulating non-tissue work pieces. Other example applications involve cosmetic improvements, imaging of human or animal anatomy, gathering data from human or animal anatomy, and training medical or non-medical personnel. Additional example applications include use for procedures on tissue removed from human or animal anatomies (without return to a human or animal anatomy), and performing procedures on human or animal cadavers. Further, these techniques can also be used for surgical and nonsurgical, medical treatment or diagnosis procedures.

Further, although some of the examples presented in this disclosure discuss teleoperational robotic systems or remotely operable systems, the techniques disclosed are also applicable to computer-assisted systems that are directly and manually moved by operators, in part or in whole. For example, these techniques can be applied to robotic systems designed to help steady a tool held by the robotic arm while the tool is manipulated by a hand of an operator. As another example, the manipulators discussed herein may be configured to allow direct manipulation, and accept operator instruction through input directly applied to a link or a joint of the manipulator.

"And/or" is used herein to indicate either or both of two stated possibilities. For example, "a position and/or orientation" is used to indicate a position, an orientation, or a combination of both position and orientation parameters.

"Pose" is used herein to indicate one or more position parameters, one or more orientation parameters, or any combination of position and orientation parameters. For example, a "pose" of the distal portion of a manipulator (or of an item held by the manipulator) can comprise one or more position parameters, one or more orientation parameters, or any combination of position and orientation parameters, of the distal portion (or of the item). Thus, although the specific examples presented in this disclosure often discuss for simplicity maintaining the position of a distal portion of a manipulator, the techniques described herein are usable in other respects as well. For example, these techniques may be used to maintain a position along one or more axes or in 3-D space, an orientation about one or more axes or in 3-D space, or a combination of position and orientation parameters for a distal portion of a manipulator, or for an item supported by the manipulator (such as a cannula or tool or other device). As a specific example, these techniques may be used to maintain a position in 3D space and a rotation in 3D space, such that no translation or rotation occurs in that 3D space.

"Reposition" is used herein to indicate changing the position, the orientation, or both the position and orientation. For example, "repositioning" of the base comprises translating or rotating the base in some way, and thus changing one or more position or orientation parameters of the base.

"Linkage" is used herein to indicate a structure comprising a single link, at least one link, or multiple links as applicable given the context.

"Tool" is used herein to encompasses both general or industrial robotic tools and specialized robotic medical instruments (including robotic surgical instruments and robotic medical instruments for diagnoses and non-surgical treatment). Examples tools (e.g. of tool **114** described in conjunction with FIG. **1**) include: cameras or other imaging tools utilizing fluoroscopic, radiation, ultrasonic, sonic, optical, or other techniques; suction, irrigation, grasping, cutting, measuring, and other tools of various sizes, shapes and functions; and tools that apply energies such as RF, microwave, ultrasound, etc.

FIG. **1** depicts a side view of a computer-assisted system in an environment **10**. In this particular example, the computer-assisted system comprises a manipulator relocation system **100**. The environment **10** may be an industrial, recreational, training, or surgical or other medical environment. The relocation system **100** includes a manipulator **102** and a controller **104**. The manipulator **102** may also be referred to as the manipulator **102**. In various implementations, the manipulator **102** is directly operated, or teleoperated in whole or in part. In various implementations, the manipulator **102** is controlled remotely. In the example shown in FIG. **1**, the manipulator **102** extends from a base **108**, at a proximal portion **110**, to a distal portion **112** that can support a tool **114**. The tool **114** may be a removable tool. In some implementations, a coupling of the manipulator provides an interface that allows the removal of the tool from the manipulator (e.g. manipulator **102** described in conjunction with FIG. **1**). For example, in some implementations, the coupling provides a tool/manipulator interface that allows rapid removal of the tool and mounting of the same tool or a different tool.

The lockable joint **106** is located proximal to a base **108** of the manipulator **102**, and is a lockable and unlockable joint. In various implementations, the lockable joint **106** is configured to be manually locked, manually unlocked, automatically locked, automatically unlocked, or a combination of the foregoing. In some implementations, the lockable joint **106** is locked at a default, and intentional or continuous input by a user is required for unlocking the lockable joint **106**. In the FIG. **1** example, the lockable joint **106** is located at the base **108**, and at the proximal portion **110** of the manipulator **102**.

Where the joint **106** is the only joint between the base **108** and a structure, locking the joint **106** locks a pose of the base **108** relative to that structure. That is, the locked pose of the base **108** is kept within narrow tolerances as limited by the design and operation of the joint **106** and the structure. Thus, the pose of the base may be referenced to a frame of reference, and held stationary relative to that frame of reference. Example frames of reference include coordinate frames fixed relative to the environment **10**, specific features of the workpiece or work site, access ports to the work site, a part of the manipulator **102** prior to repositioning, etc. If the environment **10** is a surgical or other medical environment, examples of where frames of reference may be attached include patient tissue, patient anatomical features, a surface supporting the patient, a floor surface, the surgical environment, etc.

In some implementations, the locking the joint **106** holds the base fixed relative to a reference point **118**. Where the reference point **118** is fixed relative to the environment **10**, locking the joint **106** holds the base fixed relative to the environment **10**. In some medical implementations, The reference point **118** corresponds to a point fixed relative to a workpiece **109**. The reference point **118** can, for example, correspond to a point on an insertion site or a port on the workpiece **109** through which the tool **114** is, or will be, inserted, a point fixed relative to a floor surface in the environment **10**, a point fixed relative to an operating table in the environment **10**, etc. In a surgical or other medical context, the workpiece **109** may comprise a part of a patient, and an insertion site or port may comprise an incision or natural orifice of the patient.

A powered joint **116** distal to the base **108** can be driven by an actuator operable by the controller **104** to cause relative repositioning of the base **108**, of a portion of the manipulator **102** such as the distal portion **112** of the manipulator **102**, and/or of an item coupled to the manipulator such as a cannula or the tool **114** when mounted. The powered joint **116** is positioned in kinematic series with one or more linkages of the manipulator **102**, for example, between where the tool **114** would be when supported by the manipulator **102** and the base **108**. For example, the powered joint **116** can join two of the linkages of the manipulator **102**, or join a linkage and a device mounted to the distal portion **112** of the manipulator **102**. The powered joint **116** is, in an implementation, for example, positioned between the proximal portion **110** and the distal portion **112** of the manipulator **102**. When the tool **114** is supported on the distal portion **112** of the manipulator **102**, the tool **114** and the base **108** move relative to one another when the powered joint **116** is driven. The controller **104**, for example, operates the actuator coupled to the powered joint **116** to drive the powered joint **116** and cause relative movement between the base **108** and the distal portion **112**, and hence the tool **114** if mounted to the distal portion of the manipulator **102**. During processes and operations described herein, the controller **104** operates the powered joint **116** to move the base **108** relative to the distal portion **112** (or an item coupled to the manipulator, such as a cannula or the tool **114** when mounted). To adjust the position (and/or orientation) of the base **108**, the controller **104** drives the powered joint **116** while both: (a) the joint **106** coupled to the base **108** is unlocked, and (b) a position (and/or orientation) of the distal portion **112** (or an item coupled to the manipulator) is externally maintained.

To reposition the base **108**, the controller **104** can drive the powered joint **116** by selectively activating one or more actuators that move the powered joint **116**. The driven motion of the powered joint **116** can backdrive joint **106**, and thus move the base **108**. In some cases, this backdriving of the base **108** is achieved with only the driven motion of the powered joint **116**, and no motion of any other powered joint(s) of the manipulator **102**. In some cases, this backdriving of the base **108** is achieved with the driven motion of the powered joint **116** complemented by additional driven motion of one or more other powered joint(s) of the manipulator **102**. In some cases, this backdriving of the base **108** is achieved with the backdriven motion of only the lockable joint **106**. In some cases, this backdriving of the base **108** is achieved with the backdriven motion of the lockable joint **106** and other backdriven motion of one or more other lockable joint(s) of the manipulator **102**.

Thus, the relocation system **100** is an example computer-assisted system that comprises one or more manipulators (e.g. manipulator **102**), each manipulator configured to support a tool (e.g. tool **114**). The computer-assisted system comprises one or more lockable joints (e.g. joint **116**) and a controller. (e.g. controller **104**). Each of the manipulators extends distally from a base (e.g. base **108**) and comprises a distal portion (e.g. distal portion **112**). The one or more lockable joints are coupled to the base and located proximally relative to the base. The controller **104** is operably coupled to one or more powered joints (e.g. powered joint **106**). The powered joint is located distally relative to the base. The controller **104** is configured to perform a method or a set of operations, comprising the following: driving at least one powered joint to move the distal portion while at least one lockable joint is locked, and driving at least one powered joint to move the base while at least one lockable joint is unlocked and a position of one or more distal portions are externally maintained.

In some implementations, the controller **104** drives the powered joint **106** to move the base **108** is toward a desired location (and/or orientation) for base. The desired location (and/or orientation) may be determined based on a desired motion envelope **122** or any other appropriate criteria. In some implementations, the controller **104** drives the powered joint **106** to move the base **108** toward a position (and/or an orientation) that provides a desired motion envelope **122** for the tool **114**. In some implementations, the controller **104** stops moving the base **108** once the base **108** reaches, or is within some tolerance of, the position (and/or orientation) that provides the desired motion envelope or the desired location for the base **108**. In some implementations, the controller **104** may stop driving the powered joint **116**, or stop moving the base **108**, before achieving the desired base location or the desired motion envelop **122**. Such stopping may be in response to some other criteria, such as in response to forces or deflections indicative of collision, to a determination of an inability to reach the position (and/or orientation) that provides the desired motion envelope or the desired location for the base **108**, to user input, to lack of user presence, and the like.

In some implementations, after the base has been moved by backdriving with the powered joint **116**, the lockable joint **106** is unlocked to allow driving of the powered joint **116** to move the distal portion **112** (or device held by the distal portion **112**, such as a cannula or the tool **114**). In various implementations, the lockable joint **106** is unlocked manually or in response to a user input indicating that the lockable joint should be unlocked. In some implementations, the controller **104** automatically causes the lockable joint to be unlocked automatically after achieving a desired base location or a desired motion envelope **122**. During the repositioning of the base **108**, a distal portion **112** of the manipulator **102** (or an item supported by the manipulator **102**, such as a cannula or a tool **114** if mounted to the manipulator **102**) can be externally maintained in a desired position (and/or orientation) within the environment **10**. The position (and/or orientation) may be maintained relative to any appropriate reference. In some implementations, the reference comprises a reference point (e.g. reference point **118**), one or more reference directions, or a reference frame. In some implementations, a reference consisting of a single point without orientation information can be sufficient in implementations where only position is maintained. In some implementations, the reference comprises one or more reference directions but not a reference location; for example, the one or more reference directions may be based on the three-dimensional orientation of the distal portion **112** immediately prior to a beginning of the repositioning process. A set of direction(s) without a reference location can be sufficient in implementations where only the orientation(s) corresponding to the set of direction(s) are maintained. In some implementations, the reference comprises both a reference location and one or more reference directions; such a reference may be used when position and one or more orientation parameters are maintained. In some implementations, the reference comprises a full reference frame sufficient to define location and orientation in three-dimensional space.

The position is maintained when the position is kept within an acceptable range of position changes. For example, in some implementations, the acceptable range of position changes is zero, and maintained the position involves keeping the position completely unchanged. In some implementations, the acceptable range of position changes is nonzero, and is based on the limits of the system's design; the position is maintained as close to unchanging as possible given mechanical, electrical, and computational tolerances and errors. In some implementations, the acceptable range of position changes is nonzero, and includes bounds based on operating conditions. For example, in some cases, the acceptable range of position changes is on the order of millimeters or centimeters, and is set to avoid damage to a work piece or human tissue. In some cases, the acceptable range of position changes is larger. In some cases, the acceptable range of position changes differ among different translational degrees of freedom.

Similarly, the orientation is maintained when the orientation is kept within an acceptable range of orientation changes. In various implementations, the acceptable range of orientation changes may be zero, may be a minimal amount limited by system performance, may be less than a degree or multiple degrees or larger, based on performance conditions such as avoiding damage to a work piece or human tissue, and the like. In some cases, the acceptable range of orientation changes differ among different rotational degrees of freedom.

In some implementations, the distal portion **112** of the manipulator **102** that is maintained in position (and/or orientation) comprises only part of, or all of, a distal link of the manipulator. For example, the distal portion **112** that is maintained may comprise a distal end of the distal link, may comprise a portion of the distal link configured to be adjacent an access port during a procedure, may comprise a portion of the distal link that couples to a device that mounts to the manipulator (e.g. a device such as a tool or a cannula, etc.), may comprise the entire distal link, or may comprise the entire distal link and other more distal part(s) of the manipulator **102**.

Similarly, a tool **114** or a cannula can be considered to be maintained in position (and/or orientation) when the position (and/or orientation) of a particular part of the tool **114** or cannula is maintained. In some cases, a pose of a tool **114** or a cannula is maintained by maintaining the position (and/or orientation) of a distal portion of the tool **114** or cannula, of a portion of the tool **114** or cannula adjacent to an access port, of a portion of the tool **114** or cannula that coincides with a remote center of rotation of the tool or cannula, etc.

In some examples, when the joint **106** is locked, the pose of the base **108** does not move (e.g. relative to a reference such as a reference frame anchored to the environment **10** or a reference comprising the reference point **118**). If the distal portion **112** is moveable in such an instance (e.g. free and not constrained so movable relative to the reference), the controller **104** can cause movement of the distal portion **112** relative to the reference when the powered joint **116** is driven with the joint **106** locked. When the distal portion **112** supports the tool **114**, the tool **114** moves with the distal portion **112**, and thus moves in response to the powered joint **116** being driven. The powered joint **116** is thus drivable to move the tool **114** within a motion envelope **120** defined at least in part by the position (and/or orientation) of the base **108**. The tool **114** is, for example, driven to move within the motion envelope **120** to perform an operation on target anatomy with the motion envelope **120**.

In some examples, when the joint **106** is unlocked, the pose of the base **108** is movable (e.g. relative to a reference such as a reference frame anchored to the environment **10** or a reference comprising point **118**). If the joint **106** is unlocked and a pose of the distal portion **112** of the manipulator **102** is maintained, the controller **104** can cause movement of the base **108** relative to the reference by driving the powered joint **116**. The proximal portion **110** of the manipulator **102**, for example, moves relative to the reference while the distal portion **112** of the manipulator **102** remains fixed relative to the reference. If the distal portion **112** supports the tool **114**, the tool **114** does not move as a result of movement of the distal portion **112** (since the distal portion **112** has not moved as the powered joint **116** is driven). In this regard, the controller driving the powered joint **116** results in backdriving of the proximal portion **110** and hence moves the base **108**; this causes motion of the base **108** relative to the distal portion **112** (or an item coupled to the manipulator, such as a cannula or the tool **114** when mounted), and relative to the reference.

The controller **104** can change the motion envelope of the tool **114** by driving the powered joint **116** while the joint **106** is unlocked and while the pose of the distal portion **112** (or an item coupled to the manipulator, such as a cannula or the tool **114** when mounted) is maintained. To adjust the position of the base **108**. the controller **104** drives the powered joint **116** while the base **108** is unlocked and while a position (and/or orientation) of the distal portion **112** (or an item coupled to the manipulator) is maintained relative to a reference such as a reference comprising point **118**). The base **108** moves relative to the maintained distal portion **112** (or an item coupled to the manipulator). Because the position (and/or orientation) of the distal portion **112** (or an item coupled to the manipulator) is fixed or otherwise maintained, the base **108** can be backdriven by the powered joint **116**. When the base **108** moves, the motion envelope of the tool **114** can change. A similar process can be used to adjust the orientation of the base **108**.

In various implementations, the controller **104** operates the powered joint **116** to move the base **108** in a manner toward achieving the desired motion envelope **122** for the tool **114**. In some, implementations, the desired motion envelope **122** corresponds to a motion envelope in which the tool **114** can be driven by the manipulator **102** to reach locations appropriate for the procedure. For example, the desired motion envelope **122** can correspond to a motion envelope in which an end effector of the tool **114**, or other part of the tool **114** that interacts with the workpiece or images the work site, can reach target locations for a procedure. In a medical context, the target locations may comprise target anatomy for a medical operation to be performed. In various implementations, the motion envelope is determine by the physical design, actuation limits (e.g. ranges of motion for the joints of the manipulator), pose of the manipulator **102**, location of the base **108**, etc.

The tool **114** is movable through the initial motion envelope **120** when the base **108** is at its initial pose depicted in FIG. **1**. The tool **114** is movable through the desired motion envelope **122** when the base **108** is at a final pose (not shown in FIG. **1**). The controller **104** operates the powered joint **116** to move the base **108** from its initial pose to its final pose, toward achieving the desired motion envelope **122** for the tool **114**. The motion envelopes **120**, **122** correspond to, for example, three-dimensional motion envelopes for the tool **114**, e.g., for end effectors, a distal portion, or a distal end of the tool **114**. In various implementations, the controller stops driving the powered joint **116** and/or motion of the base **108** (e.g. by actuating one or more brakes for the base **108**), when the base has reached a desired location corresponding to the desired motion envelope **122** or when the desired motion envelop **122** has been achieved. In some implementations, the controller stops driving the powered joint **116** and/or motion of the base **108** before reaching the desired base location or achieving the desired motion envelope **122**, in response to user commands or other criteria.

While the above example is described with respect to a manipulator and focuses on one powered joint **116**, various implementations may have one or many powered joints **116**. For example, in some implementations, the powered joint **116** is one of multiple powered joints **116***a*, **116***b*, **116***c* as shown in FIG. **1**. In some implementations, the powered joints **116***a*, **116***b*, **116***c* are selectively driven by the controller **104** while the joint **106** is unlocked, to move the base **108** (e.g. relative to a reference such as a reference comprising the reference point **118**). In the architecture shown in FIG. **1**, driving the powered joint **116***a* with the lockable joint **106** unlocked can move the base **108** in a first degree of freedom (DOF). Meanwhile, driving the powered joint **116***b* with the lockable joint **106** unlocked can move the base **108** in a second DOF, and driving the powered joint **116***c* with the lockable joint **106** unlocked can move the base **108** in a third DOF. The first, second, and third DOFs are different DOFs. In some implementations, the controller **104** operates the powered joints (e.g. **116***a*, **116***b*, **116***c*) contemporaneously to move the base **108** in a manner to achieve the desired motion envelope **122** for the tool **114** (or to place the base **108** into a desired location). In some implementations, the controller **104** operates the powered joints (e.g. **116***a*, **116***b*, **116***c*) separately in time, or in different combinations over time, to move the base in a piecewise temporal manner to achieve the desired motion envelope **122** for the tool **114** (or to place the base **108** into a desired location).

In some implementations, one or more powered joints **116** are driven by actuators of the manipulator **102**. In some implementations, one or more powered joints **116** are driven by one or more actuators, and these one or more actuators are in turn driven by an actuation module **402**. In some implementations, this actuation module is removably mounted to the manipulator **102**.

In the example shown in FIG. **1**, one or more powered joints **116** are driven by one or more actuators of the manipulator **102**, and one or more powered joints **116** are driven by one or more actuators for the actuation module **402**. Specifically, the powered joints **116***a*, **116***b* are powered joints of the manipulator **102**, and are driven by one or more actuators of the manipulator **102**; in contrast, the powered joint **116***c* is a powered joint of the actuation module **402**, and is driven by one or more actuators for the actuation module **402**. During an operation, the controller **104** drives the powered joints **116***a*, **116***b* and moves the actuation module **402**, thus moving the tool **114** relative to the base **108**. Further, the controller **104** drives the powered joint **116***c* to rotate the tool **114** relative to the actuation module **402**, and moves the tool **114** relative to the base **108**.

While the above example is described with respect to a manipulator with one lockable joint **106**, various implementations may have one or multiple lockable joints **106**. For example, in some implementations, the lockable joint **106** is one of multiple lockable joints **106***a*, **106***b*, **106***c*. FIG. **1** shows such an example with three lockable joints **106***a*, **106***b*, **106***c*. Specifically, in the example shown in FIG. **1**, the lockable joint **106***a* connects the manipulator **102** to a setup assembly. The lockable joint **106***b* connects linkages of the setup assembly. The lockable joint **106***c* connects the setup assembly to a support structure. In various implementations, the support structure comprises a fixture, a stand, a table or part of the table (e.g. table top, table rails, table base, table legs), etc. In some implementations, one or more of the lockable joints **106***a*, **106***b*, **106***c* are unlocked when the powered joint **116** is driven to reposition the base **108**. In some implementations with multiple lockable joints, at least one lockable joint is locked and at least one other lockable joint is unlocked for part or the entire duration when the powered joint **116** is driven to reposition the base **108**. In some implementations, selectively unlocking or locking the lockable joint **106** while driving the powered joint **116** to move the base **108** helps to guide the movement of the base **108**. For example, in some implementations, motion of the base **108** toward a desired base location or desired motion envelope **122** is achieved in a piecewise manner over time. A first combination of joints **106** are locked or unlocked to facilitate a first Then, a second, different combination of joints **106** are locked or unlocked to facilitate a second motion of the base **108** toward the desired base location or desired motion envelope **122**. The first and second motions of the base **108** may be in different directions. Additional combinations of locking or unlocking joints **106** may be utilized to provide additional motions of the base **108**.

Although FIG. **1** shows the tool **114** being supported by the manipulator **102**, and the tool **114** inserted through an access port toward the work site for a workpiece **109**, the techniques discussed can also be used to reposition the base of a system without a tool **114**, or with a tool **114** that is mounted for a procedure on a work site accessed without an access port, or with a tool **114** that is mounted but not inserted into an access port for accessing the work site. For example, the distal portion **112** of the manipulator **102** (or an item held in the distal portion **112**, such as a cannula or a tool **114**) may be externally maintained in position and/or orientation by any appropriate technique.

Example external maintenance techniques include any one or combination of: operator applied forces, fixtures, other robotic arms, access port wall forces (e.g. patient tissue forces where the work piece comprises patient anatomy) and other techniques different from driving the actuators or brakes of the manipulator **102**. Thus, the position (and/or orientation) of the distal portion **112** can be maintained directly, or indirectly through an intermediary such as an item mounted to the distal portion **112**. As a specific example, in some implementations, a pose of the distal portion **112** may be externally maintained by maintaining a position of the tool **114** when coupled to the distal portion **112** or another portion of the manipulator **102**, or of a cannula or other device coupled to the distal portion **112** or another portion of the manipulator **102**.

FIG. **2** shows an example computer-assisted system comprising a surgical system **200**. In this example, a surgeon **202** remote from the patient **209** performs a remote surgical operation by manipulating control inputs of a console **203** located remotely from the manipulator **102**. In some implementations, as shown in FIG. **2**, the environment **10** includes obstacles, e.g., operators **206**, **208**, **210**, an operation table **212**, an electronics cart **214**, surgical tool tables **216**, **218**, and other objects in the environment **10**. During operation of the manipulator **102**, the manipulator **102** may collide with an obstacle as the tool **114** is moved through its motion envelope. As described herein, to inhibit collision with an obstacle, the position (and/or orientation) of the base **108** of the manipulator **102** is adjusted to achieve a desired motion envelope based on a likelihood of collision between the manipulator **102** and the obstacle. In particular, the motion envelope of the tool **114** (shown in FIG. **1**) is adjusted to inhibit the likelihood of collision, e.g., the likelihood of collision when the tool **114** is moved through the desired motion envelope is less than the likelihood of collision when the tool **114** is moved through its initial motion envelope. This adjustment may be performed intraoperatively, defined at initial setup by using an estimate of collision probability when defining a desired motion envelope **122**, etc.

FIG. **3** is a perspective view of an example surgical environment including first and second remotely controllable manipulators. FIG. **3** is perspective view of the patient **209** on an operating table **302**. A manipulator system **300** includes a setup assembly **304** that supports the manipulator **102** relative to a reference (e.g., a reference comprising the reference point **118**) described with respect to FIG. **1**. The setup assembly **304** is mounted to a support structure **306**. In some implementations, the support structure **306** is part of the operating table **302**, e.g., is a bed rail of the operating table **302**. The support structure **306** includes a bracket **305** that fixes the setup assembly **304** to the operating table **302**. In some examples, the setup assembly **304** and/or the manipulator **102** are manually adjusted, e.g., by a human operator, to a desired pose relative to the reference point. The reference point is fixed relative to the support structure **306**. The desired pose can be selected from one of a multitude of selectable poses relative to the patient **209**. The desired pose, for example, corresponds to a pose in which an insertion axis of the tool **114** is aligned with a location of an access port through the patient body wall **20**. The operator manually manipulates the setup assembly **304** and/or the manipulator **102** to enable the tool **114** to access target anatomy through the access port.

While the setup assembly **304** is described as being rail-mounted, in some implementations, the setup assembly **304** is mounted such that the setup assembly **304** extends from an overhead frame, a floor, or other fixed portion of the surgical environment. The setup assembly **304**, for example, extends from a cart movable relative a floor of the surgical environment, and the cart includes a braking mechanism to maintain a position (and/or orientation) of the cart relative to the floor. The setup assembly **304**, for example, is mounted to a gantry movable relative to an overhead frame. The gantry moves relative to the overhead frame to reposition the setup assembly **304** relative to the patient.

The manipulator **102** is releasably and adjustably coupled to the setup assembly **304**. The base **108** of the manipulator **102**, e.g., the proximal end of the manipulator **102**, is mounted to a distal portion of the setup assembly **304**. The setup assembly **304** includes a setup joint system that couples the support structure **306**, the setup assembly **304**, and the manipulator **102**. The joint system is selectively lockable to inhibit or allow relative motion between the support structure **306** and the setup assembly **304** and/or between the manipulator **102** and the setup assembly **304**. The setup joints of the setup assembly **304** are manually adjustable. The setup assembly **304** has multiple degrees of freedom (DOFs), and is fixed stationary in a desired configuration when the joint system is locked.

The joint system includes one or more lockable setup joints. In some examples, the joint system includes lockable joints **309***a*, **309***b*, with the lockable joint **309***a* being configured to be locked to fix the setup assembly **304** relative to the support structure **306**, and the lockable joint **309***b* being configured to be locked to fix the setup assembly **304** to the manipulator **102**. The lockable joints **309***a*, **309***b* can be passive (manually adjustable) or active (power adjustable or power-assist adjustable). In the example depicted in FIG. **3**, the lockable joints **309***a*, **309***b* are manually adjustable and manually lockable.

In some implementations, one or more of the lockable joints **309***a*, **309***b* are manually lockable joints. The operator manually operates a manually operable mechanism, e.g., a knob, a lever, a switch, a button, etc., to lock a lockable joint. The manually operable mechanism, in some cases, is a purely mechanical mechanism that is manually locked to inhibit relative motion of components of the manipulator system **300**. In some cases, an electrical signal initiating a locking operation is generated when the manually operable mechanism is manually operated by the operator. The electrical signal causes the electromechanical mechanism to lock a lockable joint. In some cases, the controller **104** is configured to operate the electromechanical mechanism. The electrical signal initiating the locking operation causes the controller **104** to operate the electromechanical mechanism to lock the lockable joint. In this regard, the controller **104** is also configured to identify when the lockable joint is unlocked or when the lockable joint is locked. In some cases, the lockable joints **309***a*, **309***b* include a hydraulic locking mechanism or other mechanism to assist in locking the lockable joints **309***a*, **309***b*. A number of alternatives to this locking behavior are possible. In some cases, the lock is by default "always on," and the electrical signal initiates an unlocking operation when the manually operable mechanism is manually operated by the operator or when the controller **104** provides signals for causing such unlocking. Or, the lock is by default "always on," and the electrical signal initiates an unlocking operation when the manually operable mechanism is not manually operated by the operator, or when the controller **104** provides signals for locking or is not providing signals for unlocking.

In the example shown, a linkage **310** of the setup assembly **304** is fixed to a linkage assembly **312** of the manipulator **102** when the lockable joint **309***b* fixes the setup assembly **304** to the manipulator **102**. In particular, a distal portion of the linkage **310** is fixed to a proximal portion of the linkage assembly **312** through the lockable joint **309***b* when the lockable joint **309***b* is locked. The proximal portion of the linkage **310** is mounted to the support structure **306** through the lockable joint **309***a*. As described with respect to FIGS. **4**A to **4**C, the linkage assembly **312** includes one or more linkages that, when driven through one or more powered joints, move so as to cause relative repositioning of the base **108**, the distal portion **112**, and/or the an item coupled to the manipulator **102** such as tool **114**. The linkage assembly **312**, for example, enables yaw and pitch motion of the tool **114**.

In some implementations, one of the lockable joints **309***a*, **309***b* corresponds to the lockable joint **106** described with respect to FIG. **1**. If the manipulator system **300** is mounted to the support structure **306**, and the tool **114** is mounted to the manipulator system **300**, the tool **114** moves relative to the support structure **306** when the powered joint **116** is driven and when one or more of the lockable joints **309***a*, **309***b* are locked. For example, the lockable joint **309***a*, when locked, inhibits motion of the setup assembly **304** relative to the support structure **306** by inhibiting motion of the linkage **310** of the setup assembly **304** relative to the support structure **306**. The lockable joint **309***b*, when locked, inhibits motion of the setup assembly **304** relative to the manipulator **102** by inhibiting motion of the linkage **310** of the setup assembly **304** relative to the linkage assembly **312** of the manipulator **102**. In this regard, when the lockable joint **309***a* is unlocked, the base **108** of the manipulator **102** is movable relative to the support structure **306**, e.g., due to movement of the linkage **310** relative to the support structure **306**. When the lockable joint **309***b* is unlocked, the base **108** of the manipulator **102** is movable relative to the support structure **306**, e.g., due to movement of the linkage assembly **312** relative to the linkage **310**.

When one or both of the lockable joints **309***a*, **309***b* are unlocked and the pose of the tool **114** is maintained, the base **108** is repositioned with respect to the tool **114** (or where the tool **114** would be if mounted to the manipulator **102**) when the powered joint **116** is driven, thereby changing the motion envelope of the tool **114**. The base **108** is backdriven by the powered joint **116** so that the proximal portion **110** of the manipulator **102** is moved instead of the distal portion **112** of the manipulator **102**. The torque input at the powered joint **116** generates output movement at the base **108** rather than at the distal portion **112**.

In this example, to move the tool **114** relative to the support structure **306**, the powered joint **116** is driven with the joint system locked, e.g., with both the lockable joints **309***a*, **309***b* locked. As described herein with respect to FIGS. **4A-4C**, in some implementations, multiple powered joints are driven with the lockable joints **309***a*, **309***b* locked to move the tool **114** relative to the support structure **306**. As described herein, the powered joints can be powered joints of the manipulator **102** and/or powered joints of the actuation module **402**.

In some implementations, the manipulator system **300** is one of multiple manipulator systems **300***a*, **300***b*, where each manipulator system **300***a*, **300***b* includes a corresponding setup assembly and a corresponding remotely controllable manipulator. Both manipulator systems **300***a*, **300***b* are mounted to the support structure **306**. In some examples, multiple tools are used for a procedure. As a surgical example, multiple surgical tools are often used for a single surgical operation.

As further surgical examples, a variety of alternative computer-assisted tele-operated surgical tools of different types and differing end effectors may be used in conjunction with the techniques described herein. In some cases, the surgical tools of at least some of the manipulators are removed and replaced during a surgical procedure. In some cases, the computer-assisted tele-operated surgical tools include multiple DOFs such as, but not limited to, roll, pitch, yaw, insertion depth, opening/closing of jaws, actuation of staple delivery, activation of electro-cautery, and the like. At least some of such DOFs can be actuated by actuators of the manipulator **102** to which the surgical tool selectively coupled. Several of the end effectors, including, for example, DeBakey Forceps, microforceps, and Potts scissors include first and second end effector elements that pivot relative to each other so as to define a pair of end effector jaws. Other end effectors, including scalpels and electrocautery probes, have a single end effector element. For surgical tools having end effector jaws, the jaws will often be actuated by squeezing the grip members of input devices. In some cases, the surgical tool includes an image capture device, such as a camera.

FIG. **4A** depicts a perspective view of an example of the manipulator **102** and the tool **114** to be mounted to the manipulator **102**. The manipulator **102** may be coupled to a setup assembly such as setup assembly **304**. The manipulator **102** includes, for example, a mount **404** on the base **108** to releasably couple the setup assembly **304** to the manipulator **102**.

The base **108** is configured to releasably couple with the setup assembly **304**. The base **108** includes, for example, the mount **404**. The mount **404** couples the base **108** to the setup assembly **304** such that the base **108** is movable relative to the setup assembly **304** in three or more degrees of freedom. The mount **404** is, for example, a ball extending from a proximal end of the base **108**, the ball being configured to be received in a socket of the setup assembly **304**. The mount **404** allows for the manipulator **102** to be coupled to the setup assembly **304** in a manner such that the manipulator **102** can be reoriented relative to the setup assembly **304**. The mount **404** corresponds to, for example, the lockable joint **309***b* described with respect to FIG. **3**. When a desired orientation between the manipulator **102** and the setup assembly **304** has been attained, the mount **404** between can be releasably locked in a fixed orientation, e.g., the lockable joint **309***b* is locked. The base **108** then remains stationary relative to the setup assembly **304** until the mount **404** is unlocked.

As described herein, the distal portion **112** of the manipulator **102** is configured to be coupled to the tool **114**. The manipulator **102** includes an actuation module coupling **414** to releasably couple with an actuation module **402** to which the tool **114** is mounted. In a surgical example, the actuation module **402** comprises a surgical tool actuation module for actuating tools **114** that comprise surgical tools. The coupling **414** is configured to releasably couple with cannula **410** that is coaxial with an insertion axis **406** of the tool **114**. The cannula **410** defines a lumen that slidably receives a shaft **408** of the tool **114** (or of other devices such as, but not limited to, an endoscope) along the insertion axis **406**. For a surgical operation, the cannula **410** may comprise a patient body wall access configured to extend distally from the coupling **414** through the patient via a surgical access location on the patient body wall.

The actuation module **402** releasably receives the tool **114**. The actuation module **402** is, for example, detachable from the manipulator **102** to enable the actuation module **402** to be easily interchanged with another actuator system. When the tool **114** is mounted to the actuation module **402**, the shaft **408** of the tool **114** extends through the cannula **410**. In a surgical example, the cannula **410** extends through the patient body wall to guide the shaft **408** and an end effector **412** of the tool **114** through the patient body wall into a cavity where the end effector **412** is to perform the surgical operation. The end effector **412** is remotely controlled by the surgeon **202** (shown in FIG. **2**) when the computer-assisted tele-operated surgery is performed.

The actuation module **402** is, for example, a standalone unit including a system of actuators to control motion of the tool **114** when the tool **114** is mounted to the actuation module **402**. The manipulator **102** drives the coupling **414** to control motion of the actuation module **402** and the tool **114** mounted to the actuation module **402**. The linkage assembly **312** of the manipulator **102** is, for example, releasably coupled with the actuation module **402** through the coupling **414** so that the actuation module **402** moves when the linkage assembly **312** is operated.

Referring also to FIGS. **4**B and **4**C, the manipulator **102** includes the linkages **405***a*, **405***b*, e.g., of the linkage assembly **312**. The base **108** and the linkage **405***a* are rotatably coupled, e.g., the linkage **405***a* is rotatable relative to the base **108**. A proximal portion of the linkage **405***b* is coupled to an actuator of the manipulator **102**, e.g., positioned within the linkage **405***a*. A distal portion of the linkage **405***b* is coupled to the coupling **414**.

In some examples, the manipulator **102** includes actuators to control a first set of DOFs of the tool **114**, and the actuation module **402** includes one or more actuators to control a second set of DOFs of the tool **114**. The first set of DOFs include, for example, a pitch motion **421**, a yaw motion **422**, and a roll motion **423** of the tool **114** relative to a reference (e.g., a reference comprising the reference point **118**). The tool **114** is configured to undergo the pitch motion **421**, the yaw motion **422**, and the roll motion **423** when the tool **114** is mounted to the actuation module **402** and the actuation module **402** is mounted to the coupling **414**. The second set of DOFs of the tool **114** include, for example, an insertion motion **424** of the tool **114**. In some examples, if the end effector **412** of the tool **114** includes a DOF, the second set of DOFs further includes an end effector motion of the end effector **412**.

The controller **104** of the manipulator **102** is configured to actuate the pitch motion **421**, the yaw motion **422**, and the roll motion **423** of the coupling **414** in response to input, e.g., an input from the surgeon **202** using the surgeon console **203** as described in reference to FIG. **2**. The manipulator **102** includes two selectively operable actuators to actuate the pitch motion **421** and the yaw motion **422**, respectively. In some implementations, the manipulator **102** includes three or more selectively operable actuators. The actuation module **402** includes a selectively operable actuator to actuate the roll motion **423**. In some cases, the actuation module **402** is an integral component of the manipulator **102**, and the manipulator **102** includes the actuator to actuate the roll motion **423**. In some implementations, one of the actuators for the pitch motion **421**, the yaw motion **422**, and the roll motion **423** corresponds to an actuator of the powered joint **116** described with respect to FIG. **1**. The actuators for the pitch motion **421**, the yaw motion **422**, and the roll motion **423** are, for example, electric motors.

For the pitch motion **421**, the coupling **414** is translated along a path **418** through a slot **419** in the linkage **405***a* when an actuator (not shown) of the manipulator **102** is driven. The linkage **405***a* and the linkage **405***b* are coupled such that the linkage **405***b* is movable relative to the linkage **405***a* along the path **418** through the slot **419** in the linkage **405***a*. The coupling **414** is driven, e.g., translate along the path **418** when the actuator drives the linkage **405***b*. The path **418** corresponds to, for example, an arcuate path along which a distal portion of the linkage **405***b* travels, and the arcuate path defines a pitch arc.

For the yaw motion **422**, the linkage **405***a* is rotated relative to the base **108** about a yaw axis **420** when another actuator (not shown) of the manipulator **102** is driven. The linkage **405***a* is, for example, rotatable about the yaw axis **420** in a counterclockwise direction and/or a clockwise direction. The linkage **405***b* and the coupling **414** are rotationally coupled to the linkage **405***a* such that the linkage **405***b* and the coupling **414** rotate with rotation of the linkage **405***a*.

For the roll motion **423**, the controller **104** of the manipulator **102** is operable to drive the actuation module **402** to rotate the actuation module **402** relative to the coupling **414**. In some examples, the actuation module **402** with the tool **114** rotates when a gear fixed to the actuation module **402** is driven. The manipulator **102** includes, for example, an actuator **425** operable by the controller **104** to rotate the actuation module **402** about the insertion axis **406**.

When the controller **104** is connected to the actuation module **402**, e.g., electrically connected to the actuation module **402**, the controller **104** is configured to operate actuators of the actuation module **402**. The actuators of the actuation module **402** is operable to cause the insertion motion **424** of the tool **114** and to actuate the end effector **412** of the tool **114**. In particular, the controller **104** in response to input, e.g., an input from the surgeon **202** using the surgeon console **203** as described in reference to FIG. **2**, generates control signals to operate the actuators of the actuation module **402**. In this regard, in some examples, the manipulator **102** does not include an actuator to cause actuation of the insertion motion **424** or to actuate the end effector **412**. Rather, the actuation module **402** includes these actuators, and these actuation module **402** can be disconnected from the controller **104** to enable different actuation modules to be easily mounted to the manipulator **102**.

In some examples, to actuate the insertion motion **424** when the actuation module **402** is mounted to the manipulator **102**, the controller **104** operates an actuator of the actuation module **402** to insert the tool **114** into the patient. The actuator for the insertion motion **424** is, for example, an electric motor housed in the actuation module **402**. The tool **114** undergoing the insertion motion **424** translates through patient body tissue along the insertion axis **406**. The actuation module **402** is also operable to retract the tool **114** from the patient, e.g., translate the tool **114** away from the patient body tissue along the insertion axis **406**.

The actuation module **402** is, in some cases, operable to actuate the end effector **412** of the tool **114**. If the end effector **412** includes movable or pivotable elements, the actuation module **402** is operable to actuate the end effector **412** to cause end effector motion, e.g., to cause the end effector elements to move or pivot. If the end effector **412** includes an electrocautery device, the actuation module **402** is operable to deliver electrical energy to the electrocautery device to cauterize patient tissue. As described herein, the tool **114** may include other types of end effectors, and the actuation module **402** can accordingly include other actuation systems to operate the end effectors. The actuator for the end effector actuation depends on the type of the end effector **412**. If the end effector **412** includes movable end effector elements, the actuator is an electric motor. If the end effector **412** delivers electrical energy, the actuator is a variable power source operable to deliver electric energy to the patient tissue.

In some implementations, the manipulator **102** is a hardware-constrained remote center of motion system. The base **108** and the linkages **405***a*, **405***b* are arranged relative to one another such that the insertion axis **406** and the yaw axis **420** intersect each other at a center point of the arcuate path **418**, e.g., at a remote center of motion **426**.

The remote center of motion **426** is a point in space around which the pitch motion **421**, the yaw motion **422**, and the roll motion **423** described herein are made. For example, when the tool **114** undergoes the pitch motion **421**, the position of the remote center of motion **426** is unchanged because the center point of the arcuate path **418** is located at the remote center of motion **426**. The center point of the radius of the arcuate path **418** is, for example, coincident with the remote center of motion **426**. Hence, the pitch motion **421** of the tool **114** is made about the remote center of motion **426** because the center point of the radius of the arcuate path **418** is coincident with the remote center of motion **426**.

In some examples, as the linkage **405***a* is rotated in relation to the base **108** to generate the yaw motion **422** of the tool **114**, the position of the remote center of motion **426** is unchanged because the yaw axis **420** passes through the remote center of motion **426**. Furthermore, as the actuation module **402** is rotated in relation to the linkage **405***b* about the insertion axis **406** to generate the roll motion **423** of the tool **114**, the position of the remote center of motion **426** is unchanged because the insertion axis **406** passes through the remote center of motion **426**.

In some implementations, at all positions of the coupling **414** along the arcuate path **418**, the insertion axis **406** and the yaw axis **420** intersect each other at the center of the arcuate path **418** where the remote center of motion **426** is located. Alternatively or additionally, at all positions of the coupling **414** about the yaw axis **420** of the linkage **405***a* relative to the base **108**, the insertion axis **406** and the yaw axis **420** intersect each other at the center of the arcuate path **418** where the remote center of motion **426** is located. Further, at all positions of the coupling **414** along the arcuate path **418** in combination with any position about the yaw axis **420** of the linkage **405***a* relative to the base **108**, the insertion axis **406** and the yaw axis **420** intersect each other at the center of the arcuate path **418** where the remote center of motion **426** is located. In this regard, the motion envelope **120** of the tool **114** described with respect to FIG. **1** depends on the location of the remote center of motion **426**. The motion envelope **120**, for example, includes all possible positions of a portion of the tool **114** (such as the end effector of the tool **114**) as the tool **114** undergoes the pitch motion **421**, the yaw motion **422**, and the roll motion **423** at a given position of the remote center of motion **426**. In some implementations, the remote center of motion **426** is located at other points, e.g., at a particular distance away from the insertion axis **406**. In some implementations, the manipulator **102** is implemented using a software-constrained remote center of motion rather than, or in addition to, a remote center of motion **426**.

During an operation such as a surgical operation, the remote center of motion **426** is positioned, in some cases, coincident with a region of the cannula **410**. The remote center of motion **426** is, for example, positioned at the body wall of the patient. One advantage of such an arrangement is that while the tool **114** undergoes the pitch motion **421**, the yaw motion **422**, and/or the roll motion **423**, any resulting stress applied to the body wall by the cannula **410** is negligible because the portion of the cannula **410** that interfaces with the body wall, i.e., at the remote center of motion **426**, remains substantially stationary even while the tool **114** undergoes the motions **421**, **422**, and **423**.

FIG. **5** presents a block diagram of an example control system **500** that can be used with a computer-assisted system such as the relocation system **100**. As shown in FIG. **5**, the control system **500** includes the controller **104** and a drive system **502**. The controller **104** can operate the drive system **502** in a manner to cause relative motion of the distal portion **112** of the manipulator **102** and the base **108**. The drive system **502** includes the powered joint **116** described with respect to FIG. **1**. The powered joint **116**, for example, corresponds to a joint for one of the actuators for the pitch motion **421**, the yaw motion **422**, and/or the roll motion **423**. The powered joint **116** can be operated to actuate the pitch motion **421**, the yaw motion **422**, and/or the roll motion **423** of the tool **114** and can also be operated to actuate motion of the base **108**, e.g., to translate the base **108** in space. If the drive system **502** includes multiple powered joints to back-drive the base **108**, the base **108** can be movable in two or more dimensions. The drive system **502** includes, for example, one or more of the actuators described herein to drive the linkage assembly **312**.

In some implementations, the control system **500** includes a base locking system **504**. The controller **104** can operate the base locking system **504** in a manner to selectively fix motion of the base **108** relative to a reference (e.g., a reference comprising the reference point **118**). The base locking system **504** includes, for example, a passive or powered joint that is lockable to fix relative positions (and/or orientation)s of linkages connected at the joint. The base locking system **504** includes, for instance, the lockable joints **309***a*, **309***b*. In some cases, the controller **104** operates the base locking system **504** to selectively unlock a joint to enable relative motion of linkages connected at the joint. Alternatively, rather than being operated by the controller **104**, the base locking system **504** is operated by a human operator. A joint of the base locking system **504** includes, for instance, a manually operable locking device, e.g., a knob, a screw, etc., that, when manually operated, fixes relative motion of linkages connected at the joint to lock the joint. The manually locking device is also manually operable to unlock the joint, thereby enabling relative motion of linkages connected at the joint.

In some implementations, the control system **500** includes a sensor system **506**. The sensor system **506** includes one or more sensors to detect treatment parameters and conditions of equipment in the computer-assisted system (e.g. the surgical system **200**). In some examples, the manipulator **102** includes a pose sensor positioned at the powered joint **116** to detect relative poses of the linkages connected at the powered joint **116**. The pose sensor can include a pressure sensor, torque sensor, force sensor, position sensor, velocity sensor, accelerometer, rotary encoder, linear encoder, and/or other appropriate sensors to determine the position(s) and/or orientation(s) of linkages associated with the powered joint. The controller **104**, in some cases, determines a pose of the base **108** based on a signal from the pose sensor. In some cases, the sensor system **506** includes a pose sensor associated with the base **108**.

In some examples, the sensor system **506** includes an obstacle detection sensor. The obstacle detection sensor is positioned at one or more locations in the relocation system **100** to detect imminent collision or contact with nearby obstacles in the environment **10**. The manipulator **102**, for instance, includes an obstacle detection sensor to detect when the manipulator **102** contacts or nearly contacts nearby obstacles. The obstacles can include other equipment of the computer-assisted system (e.g. the surgical system **200**), operators within the environment **10**, or other objects within the environment **10**. The obstacle detection sensor is, for example, a contact sensor, proximity sensor, optical time-of-flight sensor, or other sensor appropriate for detecting contact with an obstacle or a distance of an obstacle. The obstacle detection sensor can also include, for example, tape switches, flexible sensing arrays, individual force sensing resistors or force sensing resistor arrays, or passive capacitive sensing systems.

The control system **500** further includes an actuation module interface **508** that enables the actuation module **402** to electrically interface with the controller **104** when the actuation module **402** is mounted to the coupling **414**. When the actuation module **402** interfaces with the controller **104** through the actuation module interface **508**, the controller **104** is capable of operating the actuators of the actuation module **402** to effect the insertion motion **424** and the end effector actuation, as described herein.

The control system **500** is operable to reposition the base **108** of the manipulator **102** by operating the powered joint **116** to backdrive the base **108**. Example processes and operations to drive the powered joint **116** to position the base **108** while maintaining the position (and/or orientation) of the distal portion **112** (and/or an item coupled to the manipulator **102** such as a cannula or the tool **114**) are described herein. FIG. **6**, for instance, depicts a flow chart of an example process **600** of relocating a manipulator such as manipulator **102**. For example, the process **600** can be used to control the powered joint **116** to backdrive the base **108**. Operations of the process **600** are, for example, performed by the controller **104**.

FIGS. **7**A and **7**B depict a specific example in which a process such as the process **600** is executed to optimize the motion envelope of the tool **114**. The manipulator **102** is operated to move the base **108** from a position (and/or orientation) in which the tool **114** has the initial motion envelope **120** (FIG. **7**A) to a position (and/or orientation) in which the tool **114** has the desired motion envelope **122** (FIG. **7**B).

The desired motion envelope **122** enables the tool **114** to more easily reach a target portion of the anatomy. In some examples, the process **600** is initiated near a beginning of a procedure, (e.g., in a surgical example, before the powered joint **116** has been operated to perform surgery on anatomy of the patient **209**). In some examples, the process **600** is initiated during a procedure, (e.g., in a surgical example, after the controller **104** has operated the powered joint **116** for a period of time to perform surgery on anatomy of the patient **209** using the tool **114**). The tool **114** is movable through the initial motion envelope **120** (FIG. **7**A) during a first portion of the procedure, and the tool **114** is movable through the desired motion envelope **122** (FIG. **7**B) through a second portion of the procedure. The process **600** is initiated after the first portion of the procedure and before the second portion of the procedure. In a surgical example, in the first portion of the surgical procedure, surgery is performed on a first part of the anatomy of the patient **209**, and in the second portion of the surgical procedure, surgery is performed on a second part of the anatomy of the patient **209**. The initial motion envelope **120** for the tool **114** can enable the tool **114** to more easily reach the first part of the anatomy, whereas the desired motion envelope **122** for the tool **114** can enable the tool **114** to more easily reach the second part of the anatomy.

During or before the process **600**, one or more lockable joints, e.g., the lockable joints **309***a*, **309***b*, are unlocked to enable the base **108** to be manually moved relative to a reference (e.g., a reference comprising the reference point **118**). The lockable joints **309***a*, **309***b*, when unlocked, enable motion of the manipulator **102** and hence motion of the actuation module **402** and the tool **114**. In some examples, while the lockable joints **309***a*, **309***b* are unlocked, the human operator **700** manipulates the lockable joints **309***a*, **309***b* to reposition the base **108**, a portion of the manipulator **102** such as the distal portion **112**, and/or an item coupled to the manipulator **102** such as a cannula or the tool **114**. The operator **700**, for example, manually grasps the actuation module **402** and/or the tool **114** and directs the tool **114** toward target anatomy of the patient **209**. In particular, the actuation module **402** is manipulated so that the insertion axis of the tool **114** is directed toward the target anatomy.

The desired motion envelope **122**, in this regard, is defined in part by the position (and/or orientation) of the tool **114** after the manual manipulation. To achieve the desired motion envelope **122** after the manual manipulation, the controller **104**, for example, executes the process **600** depicted in FIG. **6**.

At an operation **602** of the process **600**, the controller **104** determines the desired motion envelope **122** based on input data received by the controller **104**. The input data include, in some cases, instructions to initiate the operation **602** and data used to determine the manner in which the powered joint **116** should be driven. The input data correspond to data usable by the controller **104** to determine a desired motion envelope, e.g., the desired motion envelope **122**, for the tool **114**. Example types of input data include: a motion envelope or a range of motion of a setup joint for the manipulator, a type of operation to be performed, a likelihood of collision of the manipulator (such as with a person, a table, another manipulator), a pose of a second manipulator of the computer-assisted system, a pointing direction of the tool **114** (e.g. after manual manipulation to point at a target such as a portion of an industrial workpiece or target anatomy), etc. In some examples, based on the input data, the controller **104** determines the desired motion envelope **122** to be a motion envelope in which the tool **114** is centered within a range of motion of each of its DOFs. The tool **114** is, for example, centered within the roll range of motion, pitch range of motion, and roll range of motion.

In alternative or additional examples, the manipulator **102** is not optimally configured when the tool **114** is centered. The controller **104** determines a desired motion envelope **122** in which the tool **114** is not centered, e.g., biased from the center of the range of motion of each its DOFs, to improve performance of the manipulator **102** and the tool **114**. The controller **104** receives the input data and determines the desired motion envelope **122** to be a motion envelope in which the tool **114** is biased based on the input data. Examples of input data usable by the controller **104** to determine a desired motion envelope are described herein with respect to FIG. **8**.

At an operation **604**, the controller **104** drives the powered joint **116** to reposition the base **108** based on the input data received at the operation **602**. Referring to FIG. **7**A, during the operation **604**, the base **108** is repositioned relative to a reference (e.g., a reference comprising the reference point **118**) and relative to the tool **114**. The controller **104**, for example, generates control signals, and transmits the control signals to cause the drive system **502** to drive the powered joint **116**. The motion envelope of the tool **114** changes as the position (and/or orientation) of the base **108** relative to the tool **114** changes. In particular, when the relocation system **100** is in a first configuration shown in FIG. **7**A, the tool **114** has the initial motion envelope **120**. When the relocation system **100** is a second configuration shown in FIG. **7**B, the tool **114** has the desired motion envelope **120**. The controller **104** generates the control signals to achieve the desired motion envelope **122** for the tool **114** when the powered joint **116** is driven.

As shown in FIG. **7**A, the controller **104** drives the powered joint **116** while the lockable joints **309***a*, **309***b* are unlocked. To unlock the lockable joints **309***a*, **309***b*, In some examples, an operator **700** manually operates the lockable joints **309***a*, **309***b* by loosening clamping devices associated with the lockable joints **309***a*, **309***b*. In some examples, the controller **104** transmits control signals to unlock the lockable joints **309***a*, **309***b* by transmitting the control signals to brakes associated with the lockable joints **309***a*, **309***b*. The control signals release the brakes to unlock the lockable joints **309***a*, **309***b*.

The controller **104** drives the powered joint **116** while a position (and/or orientation) of the tool **114** relative to a reference (e.g., a reference comprising the reference point **118**) is maintained. As depicted in FIG. **7**A, to maintain the position (and/or orientation) of the tool **114**, In some examples, the operator **700** manually inhibits motion of the tool **114** relative to the reference by grasping onto the tool **114**, the actuation module **402**, and/or the cannula **410** to maintain the position (and/or orientation) of the tool **114** relative to the reference. In some examples, the position (and/or orientation) of the tool **114** is maintained through a fixture that inhibits motion of the tool **114**, the actuation module **402**, and/or the cannula **410**. The fixture receives and fixes the tool **114**, the actuation module **402**, and/or the cannula **410**, thereby causing the position (and/or orientation) of the tool **114** to be maintained. The fixture is, for instance, attached to an object fixed in the environment **10**, such as the support structure **306** described with respect to FIG. **3**. In some examples, the controller **104** performs the operation **604** before the tool **114** is mounted to the actuation module **402**. The actuation module **402**, is for example, mounted to the coupling **414**, and the operator **700** grasps the actuation module **402** while the controller **104** drives the powered joint **116**.

The powered joint **116** is driven while the lockable joints **309***a*, **309***b* are unlocked and while the position (and/or orientation) of the tool **114** is maintained. In this regard, the tool **114** does not move (e.g. relative to a reference) when the powered joint **116** is driven.

In the example depicted in FIGS. **7**A and **7**B, the powered joint **116** corresponds to the joint between the linkage **405***a* and the coupling **414**. Because the position (and/or orientation) of the distal portion of the linkage **405***a* relative to a reference (e.g., a reference comprising the reference point **118**) is maintained, the proximal portion of the linkage **405***a* moves relative to the reference when the powered joint **116** is driven. In this regard, portions connected in kinematic series between the support structure **306** and the proximal portion of the linkage **405***a* move when the powered joint **116** is driven. These portions include, for example, the base **108** and the setup assembly **304**. The base **108** is repositioned relative to the linkage **405***a* when the powered joint **116** is driven. If the tool **114** is centered during the operation **604**, the base **108** is moved to a desired position (and/or orientation); in some implementations, the desired position (and/or orientation) is one in which the tool **114** is at a center of the range of motion for the yaw motion **422**.

In some examples, the powered joint **116** corresponds to the joint between the linkage **405***b* and the coupling **414**. Because the position (and/or orientation) of the distal portion of the linkage **405***b* relative to a reference (e.g., a reference comprising the reference point **118**) is maintained, the proximal portion of the linkage **405***b* moves relative to the reference when the powered joint **116** is driven. In this regard, portions connected in kinematic series between the support structure **306** and the proximal portion of the linkage **405***b* move when the powered joint **116** is driven. These portions include, for example, the base **108**, the linkage **405***a*, and the setup assembly **304**. As the linkage **405***a* moves relative to the linkage **405***b*, the slot **419** in the linkage **405***a* is repositioned relative to the coupling **414**. If the tool **114** is centered during the operation **604**, the slot **419** is repositioned to a desired position (and/or orientation), for example, in which the tool **114** is at a center of the range of motion for the pitch motion **421**.

In some examples, the powered joint **116** corresponds to the joint between the actuator **425** and the actuation module **402**. Because the position (and/or orientation) of the actuation module **402** is maintained, portions connected in kinematic series between the support structure **306** and the actuator **425**. These portions include, for example, the coupling **414**, the linkage **405***b*, the base **108**, and the setup assembly **304**. The coupling **414** undergoes a roll motion when the powered joint **116** is driven, thereby causing motion of the linkage **405***b*, the linkage **405***a*, the base **108**, and the setup assembly **304**. The coupling **414** is repositioned relative to the actuation module **402** when the powered joint **116** is driven. If the tool **114** is centered during the operation **604**, the coupling **414** is moved to a desired position (and/or orientation) in which the tool **114** is, for example, at a center of the range of motion for the roll motion **423**.

In addition to the position (and/or orientation) of the tool **114**, the position (and/or orientation) of the coupling **414**, and the position (and/or orientation) of the actuation module **402** being maintained during the operation **604**, in some implementations, a position of the remote center of motion **426** and a position (and/or orientation) of the cannula **410** (shown in FIG. **4**A) relative to a reference (e.g., a reference comprising the reference point **118**) are maintained. The linkages **405***a*, **405***b*, the base **108**, and the setup assembly **304** are each movable relative to the reference during the operation **604**.

While the powered joint **116** is described as a single powered joint, in some implementations multiple powered joints of the manipulator **102** are driven to reposition portions of the manipulator **102** and the setup assembly **304** relative to the reference and the relative to the tool **114**. In this regard, the tool **114** can be centered within ranges of motion corresponding to two or more of the pitch motion **421**, the yaw motion **422**, and the roll motion **423**.

At an operation **606**, the controller **104** detects whether the desired motion envelope **122** of the tool **114** has been achieved (or, if the base **108** is in a desired location). Based on signals generated by the sensor system **506**, the controller **104** determines when the desired motion envelope **122** is achieved. The controller **104** detects, for example, whether the base **108** is in a desired location to determine whether the desired motion envelope **122** has been achieved.

If the controller **104** does not detect that the motion envelope of the tool **114** is in the desired location, the controller **104** continues driving the powered joint **116** to reposition the base **108** in the operation **604**. In some examples, the controller **104** continuously drives the powered joint **116** in the operation **604** while detecting whether the motion envelope of the tool **114** is in the desired location.

If the controller **104** detects that motion envelope of the tool **114** is the desired motion envelope **122** (e.g. of the desired shape and size, and in the desired location, or as close as achievable given particular constraints), the controller **104** indicates completion of repositioning at an operation **608**. The controller **104**, for example, issues a human-perceptible signal to the human operator to indicate the completion of the repositioning of the base **108**. The signal may include, for example, one or more of: tactile, aural, or visual indications. Some specific examples include force feedback, beeps or tones of different spatial or temporal patterns, broadcasted language, lights of different colors or spatial or temporal patterns, and textual, symbolic, or graphical feedback.

After the desired motion envelope **122** for the tool **114** has been achieved, the lockable joints **309***a*, **309***b* are locked and the manipulator **102** is ready to be operated to perform an operation on the workpiece (e.g., in a surgical example, perform a surgical operation on the target anatomy). The controller **104** drives the powered joint **116** of the manipulator **102** to perform the operation. The controller **104** operates powered joints of the manipulator **102** and/or the actuation module **402**, including the powered joint **116**. The operation of the powered joints causes the pitch motion **421**, the yaw motion **422**, the roll motion **423**, and combinations thereof, thereby moving the tool **114** to different locations within the desired motion envelope **122** to perform the operation. The controller **104** also operates the actuators of the actuation module **402** to effect the insertion motion **424** and the end effector actuation.

While the tool **114** is described to centered within a range of motion corresponding to one or more of the DOFs of the tool **114**, in some cases, the tool **114** is moved to another position (and/or orientation) within the range of motion. For example, based on the input data received at the operation **602**, the controller **104** determines the desired motion envelope **122** to be a motion envelope in which the tool **114** is biased away from the center of the range of motion of each of its DOFs.

FIG. **8** depicts examples of inputs for relocating a manipulator such as the manipulator **102**. For example, FIG. **8** depicts example input data that the controller **104** receives at the operation **602**. Input data **800** include data loaded into memory associated with the controller **104**, user-specified data, data generated by the sensor system **506**, etc. The input data **800** include, for example, procedure data **800***a*, equipment data **800***b*, pose data **800***c*, operator data **800***d*, obstacle data **800***e*, workpiece data **800***f*, and port data **800***g*. The data **800***a*, **800***b*, **800***c*, **800***e*, **800***f*, **800***g* represent some examples of the data usable by the controller **104** to control the relocation system **100**. Other types and contents of data may be appropriately used by the controller **104** to control the relocation system **100**.

The procedure data **800***a* include data indicative of the specific procedure to be performed. For example, in a surgical example, the data **800***a* includes data indicative of the surgical procedure to be performed on the patient. The procedure data **800***a* can refer to specific requirements of a workspace, such as an area around the tool **114** should be able to access (e.g., in a surgical example, an area around the patient that the tool **114** should be able to access during the surgery, due to the specific surgical procedure to be performed on the patient). A procedure may require a predetermined extent of the workspace. In some cases, the procedure data **800***a* are generated when the operator selects the extent of the workspace before the repositioning operation. The operator can select the extent of the workspace in any number of ways. For example, the operator may input the data by highlighting or tracing in a graphical user interface. As another example, an operator can move the manipulator **102** (with or without a tool being held) to indicate the workspace desired, or by moving a substitute of the tool **114** to indicate the workspace desired. Example substitutes of the tool **114** include a device that represents an average tool that may be used during the procedure, a device that replicates a proximal portion of the tool **114** but not the entire shaft and end effector, a device that projects a visual indication of locations associated with distal ends of tools that may be used during the procedure, etc. Information about the desired range of motion of the joints of the manipulator **102** or the tool **114**, or of the desired motion envelope **122**, can be derived at least in part from such a demonstration. Pose sensors of a sensor system **506**, for example, can provide data indicative of manipulator **102** configurations, tool **114** positions, or other system information form a manual demonstration by the operator of a desired workspace. The sensor system **506** can thus provide information about the desired range of motion of joints of the manipulator **102** or the tool **114**, or of the desired motion envelope **122**. The controller **104** or other computing system can then process this sensor information to determine the extent of the workspace demonstrated by the operator.

The equipment data **800***b* include data indicative of specifications of the equipment to be used during the procedure. The equipment data **800***b* can include data that specifies a range of motion for each of the joints of the manipulator system **300**, e.g., powered joints, passive joints, or both. The range of motion can be a structural or mechanical limitation. In some examples, the initial motion envelope **120** of the tool **114** is estimated based on initial positions (and/or orientations) of the joints and the ranges of motion of the joints of the manipulator **102**. The controller **104** determines desired positions (and/or orientations) for the joints within the ranges of motion that will enable the tool **114** to achieve the desired motion envelope **122**. At the operation **604**, the controller **104** drives the powered joint **116** so that the joints move toward the desired positions (and/or orientations) and the tool **114** is able to move through the desired motion envelope **122**.

The equipment data **800***b* can also include information pertaining to the type of the tool **114** mounted to the manipulator **102**. The type of the tool **114** may affect, for example, an extent of the workspace and an amount of torque necessary to perform an operation. The type of the tool **114** can be manually inputted by an operator. In some examples, the tool **114** may include a detectable tag that indicates the type of the tool **114**.

The pose data **800***c* include data indicative of poses of the joints, links, the tool, and other components of the manipulator system **300**. The pose data **800***c* includes the initial pose of each of the joints and/or links of the manipulator **102**, the initial pose of each of the joints and/or links of the setup assembly **304**, the initial pose of the tool **114**, and the initial pose of the base **108**. When the controller **104** executes the process **600** to position (and/or orient) the base **108**, as the base **108** is moved, pose sensors of the sensor system **506** can generate signals responsive to motion of the base **108**. During the procedure, based on the signals from pose sensors of the sensor system **506**, the controller **104** can control the manipulator **102** to maintain the position (and/or orientation) of the tool **114** relative to a reference (e.g., a reference comprising the reference point **118**) in accordance to remote center of motion methods described herein. In some implementations, the controller drives the powered joint **106** to move the base **108** in response to one or more signals from the sensor system **506** that indicates the position of the distal portion **112** (or device supported by the distal portion **112** such as a cannula or tool **114**) is maintained. In some implementations, the controller drives the powered joint **106** to move the base **108** in response to one or more signals from the sensor system **506** indicating that the lockable joint **116** (or combination of lockable joints) is locked.

The operator data **800***d* includes data pertaining to the operator(s). In a medical example, the operator data **800***d* includes data pertaining to the medical team, e.g., the operators, carrying out the procedure. The operator data **800***d* includes, for example, information related to the capabilities, preferences for equipment layout, levels of experience, levels of skill, and other operator-specific attributes. In some examples, an operator profile is created for each of the operators before the procedure. A team profile alternatively or additionally is created for a particular team.

The obstacle data **800***e* include data indicative of poses (e.g. one or more parameters for positions or orientations) of the patient and obstacles in the environment **10** relative to the manipulator system **300**. In some examples, the obstacle data **800***e* can include a map of the environment **10** inputted by the operator. The map can include locations of potential obstacles within the environment **10**, such as other pieces of equipment (e.g., of the surgical system **200**). The obstacle data **800***e* alternatively or additionally includes data from obstacle detection sensors of the sensor system **506**. The obstacle detection sensor can generate signals indicative of positions, orientations, or poses of obstacles within the environment **10** before the procedure, or as the manipulator **102** moves about the environment **10** during the procedure. For example, referring briefly back to FIG. **2**, in some example, the environment **10** includes multiple manipulator systems **300***a*, **300***b* or humans. The obstacle data **800***e* include locations of each of the manipulator systems **300***a*, **300***b* or humans, and the manipulator of each manipulator system **300***a*, **300***b* is repositioned based on a location of the other manipulator(s) or humans.

In some medical contexts, the workpiece data **800***f* comprises patient data and include data indicative of patient-specific characteristics. Such patient data can include data indicative of patient habitus and patient geometry. In some examples, the operator inputs the patient habitus and the patient geometry. In some cases, an imaging device can produce images that can be analyzed by the controller **104** (or by a computational system prior or during a procedure) to determine the patient habitus and the patient geometry. The imaging device may comprise part of a tool **114** or be separate from any tools **114**. The imaging device may be inserted into the patient before the base **108** is repositioned during the process **600**. The imaging device can produce images usable for estimating the patient habitus and the patient geometry. In some examples, the workpiece data **800***f* can also include data indicative of the pose of the patient relative to the manipulator **102** and/or the pose of the operating table **302** relative to the manipulator **102**. The workpiece data **800***f* can include pre-operative images, such as x-ray images, x-ray computed tomography images, magnetic resonance imaging scans, and the like. In some cases, the workpiece data **800***f* includes intraoperative images or surface scans.

The port data **800***g* include data indicative of characteristics of the access port. The port data **800***g* can indicate a position and orientation of the access port, and the position and orientation of the access port can be indicative of a position and orientation of a reference (e.g., a reference frame, a reference location, one or more reference directions, a reference comprising the reference point **118**, etc.). In some implementations, the port data is based on a pose of the manipulator **102** when a cannula coupled to the manipulator **102** is docked, when an operator indicates readiness for repositioning of the base **108**, when a tool **114** is mounted, etc. In some medical implementations, a component such as the cannula **158** or the tool **114** is inserted through the access port on the patient, and the controller **104** can determine the position and orientation of the access port based on signals from sensors on the manipulator **102**.

In some examples, the port data **800***g* can be inputted by the operator. If the tool **114** is not inserted into the access port before the controller **104** executes the process **600** to position (and/or orient) the base **108**, the controller **104** can select the reference based on the inputted port data **800***g*. The reference is selected such that the tool **114** is positioned and oriented to be easily inserted into the access port after the positioning (and/or orienting) of the base **108** is complete. In particular, the tool **114** can be in a retracted position or configuration during the positioning (and/or orienting) of the base **108** and then translated axially to an insertion position such that the reference corresponds to the position (and/or orientation) of the access port.

In some implementations, one or more of the indices **805** can be selected, e.g., by the operator or in accordance to a default setting, to be optimized by the controller **104**. The controller **104** optimizes the selected indices **805** by determining an optimal configuration for the relocation system **100**. When the relocation system **100** is in the optimal configuration, the tool **114** has the desired motion envelope **122**. In some cases, the controller determines the desired motion envelope **122** based on optimizing the indices and then determines the optimal configuration for the relocation system **100** to achieve the desired motion envelope **122**. After determining the optimal configuration of the relocation system **100**, the controller **104** generates output signals **810** to operate the manipulator **102** to achieve the optimal configuration and thereby achieve the desired motion envelope **122**

As shown in FIG. **8**, the indices **805** include, for example, a range of motion index **805***a*, a stability index **805***b*, a smoothness index **805***c*, a torque index **805***d*, an obstacle index **805***e*, and a workpiece force index **805***f*. Other indices may be appropriate. Each of the indices **805** represent an optimization goal for the controller **104**. Based on the input data **800**, the controller **104** computes values for one or more indices **805**. The values for the indices are, for example, functions of the input data **800**. The controller **104** can optimize the functions for the values of the indices based on the input data **800** received at the operation **602**. The controller **104**, for example, determines an optimal configuration for the relocation system **100** to optimize the functions. The controller **104**, for example executes optimization strategies to determine the desired motion envelope **122** that optimizes the values for the selected indices. The optimization strategies include, for example, a gradient descent-based optimization strategy, a least squares-based optimization strategy, or other appropriate strategies. In some implementations, an optimization strategy for an operation is based on data from previous similar operations. The data from the previous operations include, for example, inputs collected during the previous operations, indices determined during the previous operations, and/or scores determined during the previous operations. In some cases, the optimization strategy is determined using a machine learning approach, such as, for example, artificial neural networks or expert systems.

The input data **800** and the indices **805** can be continually updated as the controller **104** performs the operation **604**. In this regard, the controller **104** can continuously receive the input data at the operation **602** as the controller **104** drives the powered joint **116** at the operation **604**. The values of the indices **805** can change as, for example, sensors of the sensor system **506** generate conditions of the environment **10** and of the relocation system **100**. The desired motion envelope **122** can thus continuously change as the controller **104** drives the powered joint **116** and new input data is received by the controller **104**.

In some examples, a single index is selected as a primary goal, and the desired motion envelope **122** is determined based on optimizing the value of single index. In some cases, a second index is selected as a secondary goal, and the desired motion envelope **122** is determined based on optimizing both the value of the first index and the value of the second index. In some examples, multiple indices are selected, and a weight is assigned to each of the selected indices. The weight is indicative of a priority of the index relative to other selected indices. A score is computed based on the weight for each selected index and the value for each selected index. The desired motion envelope **122** is determined based on optimizing the score.

A value of the range of motion index **805***a* is determined based on the range of motion available for each of the joints. The value of the range of motion index **805***a* may be computed based on, for example, the equipment data **800***b* and the pose data **800***c*. For example, the controller **104** can determine an amount of motion available in each of the two directions of a DOF for the current configuration of the manipulator **102**, e.g., for the pitch motion **421**, the yaw motion **422**, or the roll motion **423**. In some cases, the controller **104** determines the desired motion envelope **122** such that the tool **114** is movable a substantially equal amount in both directions of a DOF. In some examples, if the range of motion index **805***a* corresponds to the only index to be optimized, the desired motion envelope **122** is selected such that the tool **114** is centered with respect to each of its DOFs.

A value of the stability index **805***b* is determined based on the pose data **800***c* to determine the stability of the tool **114** in the current pose of the tool **114**. The value of the stability index can be computed based on an amount of movement of the tool **114** while the base **108** is being repositioned. For example, during the positioning (and/or orienting) of the base **108**, if the pose sensor of the sensor system **506** detects large movement distance, speed, or acceleration of the distal portion of the manipulator **102** (or of a cannula or tool **114** or other item mounted to the manipulator **102**), the controller **104** can determine that the stability index is suboptimal. The value of the stability index **805***b* can thus vary during the course of the operation **604** as the sensor system **506** detects instability of the tool **114**.

Alternatively or additionally, the controller **104** determines if the position and/or orientation of the distal portion of the manipulator **102** (or of a device held by the manipulator **102** such as a cannula or a tool **114**) is not maintained relative to the reference. And, if the position and/or orientation is not maintained within a threshold or other maintenance criteria, the controller **104** can slow or stop further repositioning of the base **108**. The controller **104** can also issue an alert to the operator to provide sufficient external maintenance of the position and/or orientation of the distal portion of the manipulator **102** (or of a device held by the manipulator **102**).

In some implementations, the controller **104** slows, stops, or otherwise inhibits motion of the base **108** in response to a determination that a motion envelope of the tool is approaching a desired motion envelope **122** for the tool or if the base **108** is approaching a desired base location.

A value of the smoothness index **805***c* is indicative of the motion performance of the tool **114** and, in some cases, the motion performance of some or all of the joints of the manipulator **102**. The controller **104** can estimate the motion performance by determining a resolution of motion of the tool **114** that is possible for the current pose of the manipulator **102** and the tool **114**. For example, for a particular joint, actuation of the joint by an increment (e.g., a given applied voltage) may result in an amount of motion of the tool **114** that depends on the pose of each of the joints of the manipulator **102** and the pose of the tool **114**. In some implementations, the value of the smoothness index **805***c* is computed based on the spatial resolution achievable as a function of pose and joint sensor position resolution. The smoothness index **805***c* can account for the size of the motion caused by the incremental voltage applied. In this regard, a smaller motion of the tool **114** from a given applied incremental voltage can result in improved motion performance of the tool **114** and greater smoothness of motion. The controller **104** can compute the value of the smoothness index **805***c* based on, for example, the equipment data **800***b* and the pose data **800***c*.

A value of the torque index **805***d* for the tool **114** is indicative of a torque that the manipulator **102** can exert on the tool **114**. In some implementations, the procedure may require that the manipulator **102** be able to manipulate the tool **114** with a minimum torque necessary to perform the procedure. It may be beneficial in these cases to maximize the torque achievable by the tool **114**. The achievable torque, however, can depend on the positions and orientations of the joints relative to the tool **114** as well as the position (and/or orientation) of the base **108** relative to the tool **114**. The controller **104** can compute the value of the torque index based on, for example, the procedure data **800***a*, the equipment data **800***b*, and the pose data **800***c*.

In some implementations, instead of or in addition to a torque index, a force index indicative of a force that the manipulator **102** can exert on the tool **114** is computed. Furthermore, the torque index and/or the force index may account for forces and torques on joints of the manipulator system **300** such that forces and/or torques on a particular joint can be minimized during motion of the manipulator **102** within the workspace.

A value of the obstacle index **805***e* is determined based on the pose data **800***c* and the obstacle data **800***e*. The obstacle index represents a likelihood that the manipulator **102** may collide with nearby obstacles. In this regard, using the obstacle data **800***e*, the current pose of the manipulator **102**, and the procedure data **800***a*, the controller **104** can compute the value of the obstacle index **805***e* to determine whether the manipulator **102** may collide with a nearby obstacle. The value of the obstacle index **805***e* may vary over the course of the operation **604** as new obstacles are detected by the sensor system **506**.

A value of the workpiece force index **805***f* is indicative of an amount of force applied to, or applied by, the workpiece. For example, the value of the workpiece force index **805***f* may be computed based on the pose data **800***c*, the workpiece data **800***f*, and the port data **800***g*, and may be indicative of an amount of torque or force that may be exerted on a workpiece. The controller **104** can use the workpiece force index **805***f* to determine if the manipulator **102** or the base **108** are being moved in a manner that may apply force exceeding a desired amount on the workpiece. In a medical context, the workpiece force index **805***f* may indicate an amount of force applied to, or by, patient tissue. The controller **104** can use the workpiece force index **805***f* in determining if the force applied exceeds a threshold force for applying to the tissue of the patient.

Controllers and any associated components described herein can be part of a computing system that facilitates control of the insertion systems according to processes and methods described herein. FIG. **9** is a schematic diagram of an example of a computer system **900** that can be used to implement a controller, e.g., the controller **104**, described in association with any of the computer-implemented methods described herein. The system **900** includes components such as a processor **910**, a memory **920**, a storage device **930**, and an input/output device **940**. Each of the components **910**, **920**, **930**, and **940** are interconnected using a system bus **950**. The processor **910** is capable of processing instructions for execution within the system **900**. In some examples, the processor **910** is a single-threaded processor, while in some cases, the processor **910** is a multi-threaded processor. The processor **910** is capable of processing instructions stored in the memory **920** or on the storage device **930** to display graphical information for a user interface on the input/output device **940**.

Memory storage for the system **900** can include the memory **920** as well as the storage device **930**. The memory **920** stores information within the system **900**. The information can be used by the processor **910** in performing processes and methods described herein. In some examples, the memory **920** is a computer-readable storage medium. The memory **920** can include volatile memory and/or non-volatile memory. The storage device **930** is capable of providing mass storage for the system **900**. In general, the storage device **930** can include any non-transitory tangible media configured to store computer readable instructions. Optionally, the storage device **930** is a computer-readable medium. Alternatively, the storage device **930** may be a floppy disk device, a hard disk device, an optical disk device, or a tape device. This, the system **900** comprises a non-transitory machine-readable medium; the medium stores a plurality of machine-readable instructions which when executed by one or more processors (e.g. processor **910**) are adapted to cause the one or more processors to perform a method or operations (e.g. any of the methods or operations described herein) for a computer-assisted system (e.g. the relocation system **100** or any other computer-assisted system described herein).

In some cases, the processor **910** is in communication with a remote computing system **935**. The remote computing system **935** includes, for example, a remote server, a cloud computing device, or other computing device remote from the processor **910** and its systems. The remote computing system **935** includes computing resources remote from the environment of the processor **910**, e.g., remote from the environment. In some cases, the remote computing system **935** includes one or more servers that establish wireless links with the processor **910**. The remote computing system **935** includes, for example, a portion of a network-accessible computing platform implemented as a computing infrastructure of processors, storage, software, data access, and so forth accessible by the processor **910**.

The system **900** includes the input/output device **940**. The input/output device **940** provides input/output operations for the system **900**. In some examples, the input/output device **940** includes a keyboard, a computer mouse, a pointing device, a voice-activated device, a microphone, a touch-screen, etc. In some cases, the input/output device **940** includes a display unit for displaying graphical user interfaces.

The features of the methods and systems described in this application can be implemented in digital electronic circuitry, or in computer hardware, firmware, or in combinations of them. The features can be implemented in a computer program product tangibly stored in an information carrier. The information carrier can be, for example, a machine-readable storage device, for execution by a programmable processor. Operations can be performed by a programmable processor executing a program of instructions to perform the functions described herein by operating on input data and generating output. The described features can be implemented in one or more computer programs that are executable on a programmable system including at least one programmable processor coupled to receive data and instructions from, and to transmit data and instructions to, a data storage system, at least one input device, and at least one output device. A computer program includes a set of instructions that can be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program can be written in any form of programming language, including compiled or interpreted languages. The computer program can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. The computer program implements, for example, a fast genetic algorithm (FGA).

Generally, a computer will also include, or be operatively coupled to communicate with, one or more mass storage devices for storing data files. Such devices can include magnetic disks, such as internal hard disks and removable disks, magneto-optical disks, and optical disks. Storage devices suitable for storing the computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices, magnetic disks such as internal hard disks and removable disks, magneto-optical disks, and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

To provide for interaction with a user, the features can be implemented on a computer having a display device such as a CRT (cathode ray tube) or LCD (liquid crystal display) monitor for displaying information to the user and a keyboard and a pointing device such as a mouse or a trackball by which the user can provide input to the computer. Alternatively, the computer can have no keyboard, mouse, or monitor attached and can be controlled remotely by another computer.

The features can be implemented in a computer system that includes a back-end component, such as a data server, or that includes a middleware component, such as an application server or an Internet server, or that includes a front-end component, such as a client computer having a graphical user interface or an Internet browser, or any combination of them. The components of the system can be connected by any form or medium of digital data communication such as a communication network. Examples of communication networks include, e.g., a LAN, a WAN, and the computers and networks forming the Internet.

The computer system can include clients and servers. A client and server are generally remote from each other and typically interact through a network. The relationship of client and server arises by virtue of computer programs running on the respective computers and having a client-server relationship to each other.

The processor **910** carries out instructions related to a computer program. The processor **910** can include hardware such as logic gates, adders, multipliers and counters. The processor **910** can further include a separate arithmetic logic unit (ALU) that performs arithmetic and logical operations.

A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made. For example, the computer-assisted system may comprise one or more manipulators with redundant degrees of freedom. These manipulators, in some cases, are referred to as having excess, extra, or redundant degrees of freedom. A manipulator with redundant degrees of freedom has an architecture with more degrees of freedom than necessary to place the distal portion of the manipulator (e.g. manipulator **102**) or a tool or other device mounted on the manipulator, if present (e.g. tool **114** or a cannula or other device in a given position. For example, in some implementations, the manipulator include a kinematic chain comprising a plurality of joints and links that provide sufficient degrees of freedom to allow a range of joint states for (1) a pose of the base (e.g. the base **108**) and (2) a state of a distal portion (e.g. distal portion **112**) of the manipulator (e.g. the manipulator **102**) or of an end effector of a tool (e.g. tool **114**) supported by the manipulator. In manipulators with redundant degrees of freedom, actuation of one joint may be directly replaced by a similar actuation of a different joint along the kinematic chain. Thus, one or more intermediate links or joints may be moved without changing a pose of the distal portion or a tool or other device mounted on the manipulator.

Accordingly, other implementations are within the scope of the claims.

What is claimed is:

1. A computer-assisted system comprising:
- a manipulator configured to support a tool, the manipulator extending distally from a base and comprising a distal portion;
- a lockable joint coupled to the base and located proximally relative to the base; and
- a controller operably coupled to a powered joint, the powered joint located distally relative to the base, wherein the controller is configured to perform operations comprising:
  - driving the powered joint to move the distal portion while the lockable joint is locked, and
  - driving the powered joint to move the base while the lockable joint is unlocked and a position of the distal portion is externally maintained.

2. The computer-assisted system of claim **1**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:
- driving the powered joint while both the position and an orientation of the distal portion are externally maintained.

3. The computer-assisted system of claim **1**, wherein driving the powered joint to move the base changes a motion envelope of the distal portion or the tool.

4. The computer-assisted system of claim **1**, wherein:
- the position of the distal portion is externally maintained relative to a location of an access port through which the tool accesses a work site;
- driving the powered joint to move the distal portion while the lockable joint is locked comprises:
- moving the distal portion relative to the location of the access port; and
- driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:
- moving the base relative to the location of the access port.

5. The computer-assisted system of claim **1**, wherein driving the powered joint to move the distal portion while the lockable joint is locked comprises:
- driving the powered joint to move the distal portion while a position of the base is maintained by the lockable joint.

6. The computer-assisted system of claim **1**, wherein the position of the distal portion is externally maintained by maintaining a position of the tool or a position of a cannula coupled to the manipulator.

7. The computer-assisted system of claim **1**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:
- backdriving with the powered joint.

8. The computer-assisted system of claim **1**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:
- slowing or stopping motion of the powered joint in response a determination that the position of the distal portion is not externally maintained.

9. The computer-assisted system of claim **1**, wherein the manipulator is configured to couple to an actuation module and to support the tool through the actuation module, wherein the actuation module is operable to drive the tool, and wherein the actuation module comprises the powered joint.

10. The computer-assisted system of claim **1**, wherein the manipulator comprises the powered joint.

11. The computer-assisted system of claim **1**, wherein the operations further comprises:
- driving the powered joint to center the tool within a range of motion of the tool.

12. The computer-assisted system of claim **1**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:
- determining a desired motion envelope based on a type of operation to be performed, a likelihood of collision of the manipulator, or a pose of the manipulator relative to a pose of a second manipulator of the computer-assisted system; and
- driving the powered joint to move the base toward a position that provides the desired motion envelope.

13. The computer-assisted system of claim **1**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:
- driving the powered joint to adjust a position of the base based on a pointing direction of the tool.

14. The computer-assisted system of claim **1**, further comprising:
- a setup assembly configured to couple the base to a table, the setup assembly comprising the lockable joint.

15. The computer-assisted system of claim **1**, further comprising a sensor configured to generate a signal in response to detecting that the position of the distal portion is externally maintained, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:

driving the powered joint to move the base in response to the signal.

16. The computer-assisted system of claim **1**, wherein the operations further comprises:

unlocking the lockable joint after driving the powered joint to move the base.

17. The computer-assisted system of claim **1**, wherein the operations comprise:

selectively unlocking or locking the lockable joint while driving the powered joint to move the base while the position of the distal portion is externally maintained.

18. The computer-assisted system of claim **1**, wherein the operations further comprises:

inhibiting motion of the base in response to a determination that a motion envelope of the tool is approaching a desired motion envelope for the tool.

19. A method for operating a computer-assisted system, the computer-assisted system comprising a manipulator and a lockable joint, the manipulator extending distally from a base, the lockable joint coupled to the base and located proximally relative to the base, the method comprising:

driving a powered joint to move the base while the lockable joint is unlocked and a position of a distal portion of the manipulator is externally maintained, wherein the powered joint located distally relative to the base; and

driving the powered joint to move the distal portion while the lockable joint is locked.

20. The method of claim **19**, further comprising:

determining a desired motion envelope for a tool supported by the manipulator, wherein

driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion of the manipulator is externally maintained comprises:

moving the base such that a motion envelope of the tool is adjusted based on the desired motion envelope.

21. The method of claim **19**, wherein driving the powered joint while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:

backdriving with the powered joint.

22. The method of claim **19**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:

slowing or stopping motion of the powered joint in response a determination that the position of the distal portion is not externally maintained.

23. The method of claim **19**, wherein the manipulator is configured to support a tool, the method further comprising:

driving the powered joint to center the tool within a range of motion of the tool.

24. The method of claim **23**, wherein driving the powered joint to center the tool within the range of motion of the tool comprises:

driving the powered joint to adjust a position of the base based on a pointing direction of the tool.

25. A non-transitory machine-readable medium comprising a plurality of machine-readable instructions which when executed by one or more processors are adapted to cause the one or more processors to perform a method for operating a computer-assisted system, the computer-assisted system comprising a manipulator and a lockable joint, the manipulator extending distally from a base, the lockable joint coupled to the base and located proximally relative to the base, wherein the method comprises:

determining a desired location for the base;

driving a powered joint to backdrive the base toward the desired location while the lockable joint is unlocked and a position of a distal portion of the manipulator is externally maintained, wherein the powered joint is located distally relative to the base; and

after the lockable joint is locked, driving the powered joint to move the distal portion.

26. The non-transitory machine-readable medium of claim **25**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:

driving the powered joint while both the position and an orientation of the distal portion is externally maintained.

27. The non-transitory machine-readable medium of claim **25**, wherein driving the powered joint to move the base while the lockable joint is unlocked and the position of the distal portion is externally maintained comprises:

backdriving with the powered joint; and

slowing or stopping motion of the powered joint in response a determination that the position of the distal portion is not externally maintained.

* * * * *